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Department of Mechanical Engineering

Study Material: MEC 452 PRODUCT DESIGN AND DEVELOPMENT

B Tech 8th sem MECHANICAL ENGINEERING D156

BOOK: Product design and development by Ulrich -Mc Graw Hill

Only for Reference

CHAPTER ELEVEN

Industrial Design

EXHIBIT 11-1
Evolution of Motorola flip phones. Shown (clockwise from top left) are the MicroTAC (1989), StarTAC (1993), V60 (2001), and RAZR (2004) models.

Courtesy of Motorola Inc.

In 2003, Motorola launched a product development effort to augment its very successful but aging lines of flip-style (or clamshell) mobile telephones with an exciting new product. The StarTAC and V-series platforms had each seen several generations of products released since the early 1990s, eventually including models for every major worldwide market and standard.

The RAZR design emerged from a product vision to be "thin to win"—considerably thinner than other mobile telephones on the market and striking in its iconic new form. This design required a new architecture, entirely distinct from the existing product platforms. Upon its introduction in 2004, customers judged the ultra-thin RAZR design, shown in Exhibit 11-1, to be just as radical as its Motorola flip-phone predecessors when they were released.

Sales to early adopters came quickly after a successful market introduction in which Hollywood celebrities were shown with the product. Surpassing Motorola's expectations, RAZR sales reached millions of units within one year of launch. This success can be attributed to several factors:

- ***Small size and weight:*** With its slimmer form factor, the RAZR was "more pocketable" than other mobile phone models. The RAZR had a thickness of 14 millimeters and a weight of 95 grams, making it the thinnest and one of the lightest mobile phones on the market at the time.
- ***Performance features:*** The RAZR featured an integrated VGA camera; a large, backlit keypad; and a large, bright, color display for new video and graphic applications. Instead of a headset jack, the RAZR utilized Bluetooth networking for wireless headset accessories. Superior signal reception and transmission were achieved with a novel layout in which the phone's antenna was positioned below the keypad and away from the user's fingers, which can block weak signals.
- ***Superior ergonomics:*** The RAZR's sleek, ergonomic design complemented the human face. The shape of the handset, particularly the angled position of the display with respect to the keypad section, conformed to the user for superior comfort. The spacing and position of the buttons on the keypad were based on accepted standards, and extensive testing allowed for fast and accurate dialing. The folding design allowed the user to answer or end calls by opening or closing the phone with one hand, aided by a recess between the two sections of the clamshell. New software for navigation and new shortcuts for entering text facilitated use of text messaging and other applications.
- ***Durability:*** As with all Motorola products, the RAZR was designed to meet rigorous specifications. It could be dropped from a height of more than 1 meter onto a cement floor or sat upon in the open position without sustaining any damage. The RAZR could also withstand temperature extremes, humidity, shock, dust, and vibration.
- ***Materials:*** The RAZR utilized several advanced materials to enhance both performance and appearance. These included a laser-cut keypad with laser-etched patterns, magnesium hinge, ultra-thin anodized aluminum housing, polycarbonate composite antenna housing, and chemically annealed glass with a thin-film coating.
- ***Appearance:*** The sleek design and metallic finishes gave the RAZR a futuristic look associated with innovation. Because of its aesthetic appeal and highly recognizable appearance, the RAZR quickly became somewhat of a status symbol for early adopters and created strong feelings of pride among owners.

The RAZR development team included electrical, mechanical, materials, software, and manufacturing engineers, whose contributions were instrumental in developing the technologies and manufacturing processes that allowed the product to achieve its form factor, performance, and weight. However, without the contributions of industrial designers, who defined the size, shape, and human factors, the RAZR would never have taken its innovative, ultra-thin form. In fact, the Motorola team could easily have developed "just another phone," smaller and lighter than the previous flip-phone models. Instead, a revolutionary concept generated by the industrial designers on the team turned the project into a dramatic success.

Industrial designers are primarily responsible for the aspects of a product that relate to the user's experience—the product's aesthetic appeal (how it looks, sounds, feels, smells) and its functional interfaces (how it is used). For many manufacturers, industrial design has historically been an afterthought. Managers used industrial designers to style, or "gift wrap," a product after its technical features were determined. Companies would then market the product on the merits of its technology alone, even though customers certainly evaluate a product using more holistic judgments, including ergonomics and style.

Today, a product's core technology is generally not enough to ensure commercial success. The globalization of markets has resulted in the design and manufacture of a wide array of consumer products. Fierce competition makes it unlikely that a company will enjoy a sustainable competitive advantage through technology alone. Accordingly, companies such as Motorola are increasingly using industrial design as an important tool for both satisfying customer needs and differentiating their products from those of their competition.

This chapter introduces engineers and managers to industrial design (ID) and explains how the ID process takes place in relation to other product development activities. We refer to the RAZR example throughout this chapter to explain critical ideas. Specifically, this chapter presents:

- A historical perspective on ID and a working definition of ID.
- Statistics on typical investments in ID.
- A method for determining the importance of ID to a particular product.
- The costs and benefits of investing in ID.
- How ID helps to establish a corporation's identity.
- Specific steps industrial designers follow while designing a product.
- A description of how the ID process changes according to product type.
- A method for assessing the quality of the ID effort for a completed product.

What Is Industrial Design?

The birth of ID is often traced to western Europe in the early 1900s. (See Lorenz, 1986, for an account of the history of ID, which is summarized here.) Several German companies, including AEG, a large electrical manufacturer, commissioned a multitude of craftspeople and architects to design various products for manufacture. Initially, these early European designers had little direct impact on industry; however, their work resulted in lasting theories that influenced and shaped what is today known as industrial design.

Early European approaches to ID, such as the Bauhaus movement, went beyond mere functionalism; they emphasized the importance of geometry, precision, simplicity, and economy in the design of products. In short, early European designers believed that a product should be designed "from the inside out." Form should follow function.

In the United States, however, early concepts of ID were distinctly different. While early European industrial designers were architects and engineers, most industrial designers in America were actually theater designers and artist-illustrators. Not surprisingly, ID in the United States was often at the service of sales and advertising, where a product's exterior was all important and its insides mattered little. Pioneers in U.S. industrial design, including Walter Dorwin Teague, Norman Bel Geddes, and Raymond Loewy, emphasized streamlining in product design. This trend is best evidenced in U.S. products of the 1930s. From fountain pens to baby buggies, products were designed with nonfunctional aerodynamic shapes in an attempt to create product appeal. The auto industry provides another example. The shapes of European automobiles of the 1950s were fairly simple and smooth, while U.S. cars of the same era were decorated with such nonfunctional features as tailfins and chrome teeth.

By the 1970s, however, European design had strongly influenced American ID, largely through the works of Henry Dreyfuss and Eliot Noyes. Heightened competition in the marketplace forced companies to search for ways to improve and differentiate their products. Increasingly, companies accepted the notion that the role of ID needed to go beyond mere shape and appearance. Success stories such as Bell, Deere, Ford, and IBM, all of which effectively integrated ID into their product development process, helped further this thinking.

By 2000, industrial design became widely practiced in the United States by professionals in many diverse settings ranging from small design consulting firms to in-house design offices within large manufacturing companies. Motorola's industrial designers comprise a department titled "consumer experience design" and participate fully in all new product development efforts.

The Industrial Designers Society of America (IDSA) defines industrial design as "the professional service of creating and developing concepts and specifications that optimize the function, value, and appearance of products and systems for the mutual benefit of both user and manufacturer." This definition is broad enough to include the activities of the entire product development team. In fact, industrial designers focus their attention upon the form and user interaction of products. Dreyfuss (1967) lists five critical goals that industrial designers can help a team to achieve when developing new products:

- ***Utility:*** The product's human interfaces should be safe, easy to use, and intuitive. Each feature should be shaped so that it communicates its function to the user.
- ***Appearance:*** Form, line, proportion, and color are used to integrate the product into a pleasing whole.
- ***Ease of maintenance:*** Products must also be designed to communicate how they are to be maintained and repaired.
- ***Low costs:*** Form and features have a large impact on tooling and production costs, so these must be considered jointly by the team.
- ***Communication:*** Product designs should communicate the corporate design philosophy and mission through the visual qualities of the products.

Industrial designers are typically educated in four-year university programs where they study sculpture and form; develop drawing, presentation, and model-making skills; and gain a basic understanding of materials, manufacturing techniques, and finishes. In industrial practice, designers receive additional exposure to basic engineering, advanced manufacturing/fabrication processes, and common marketing practices. Their ability to express ideas visually can facilitate the process of concept development for the team. Industrial designers may create most of the concept sketches, models, and renderings used by the team throughout the development process, even though the ideas come from the entire team.

Assessing the Need for Industrial Design

To assess the importance of ID to a particular product, we first review some investment statistics and then define the dimensions of a product that are dependent upon good ID.

Expenditures for Industrial Design

Exhibit 11-2 shows approximate values of investment in ID for a variety of products. Both the total expenditures on ID and the percentage of the product development budget invested in ID are shown for consumer and industrial products spanning various industries. These statistics should give design teams a rough idea of how much ID investment will be required for a new product.

The exhibit shows that the range of expenditures on ID is tremendous. For products with relatively little user interaction such as some types of industrial equipment, the cost of ID is only in the tens of thousands of dollars. On the other hand, the development of an intensely visual and interactive product such as an automobile requires millions of dollars of ID effort. The relative cost of ID as a fraction of the overall development budget also shows a wide range. For a technically sophisticated product, such as a new aircraft, the ID cost can be insignificant relative to the engineering and other development expenditures. This does not suggest, however, that ID is unimportant for such products; it suggests only that the other development functions are more costly. Certainly the success of a new automobile design is highly dependent on its aesthetic appeal and the quality of the user interfaces, two dimensions largely determined by ID; yet the ID expense of $10 million is modest, relative to the entire development budget.

How Important Is Industrial Design to a Product?

Most products on the market can be improved in some way or another by good ID. All products that are used, operated, or seen by people depend critically on ID for commercial success.

With this in mind, a convenient means for assessing the importance of ID to a particular product is to characterize importance along two dimensions: ergonomics and aesthetics. (Note that we use the term *ergonomics* to encompass all aspects of a product that relate to its human interfaces.) The more important each dimension is to the product's success, the more dependent the product is on ID. Therefore, by answering a series of questions along each dimension we can qualitatively assess the importance of ID.

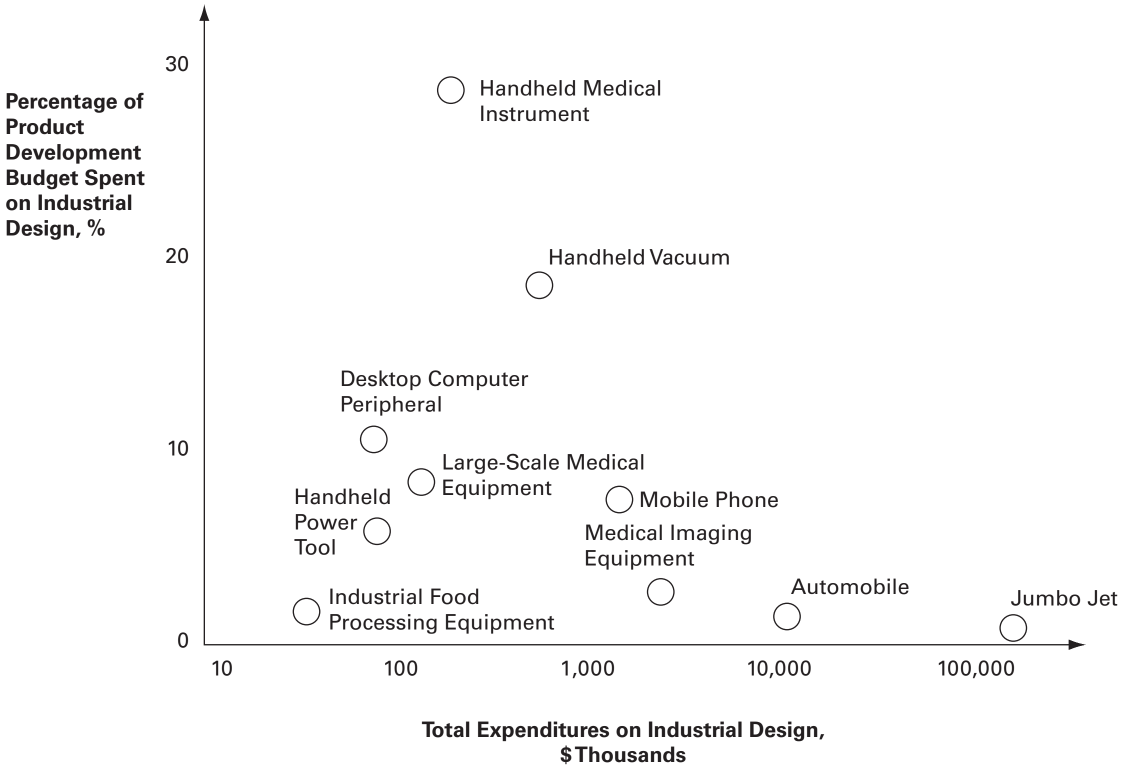


EXHIBIT 11-2 Industrial design expenditures for some consumer and industrial products.

Ergonomic Needs

- ***How important is ease of use?*** Ease of use may be extremely important both for frequently used products, such as an office photocopier, and for infrequently used products, such as a fire extinguisher. Ease of use is more challenging if the product has multiple features and/or modes of operation that may confuse or frustrate the user. When ease of use is an important criterion, industrial designers will need to ensure that the features of the product effectively communicate their function.
- ***How important is ease of maintenance?*** If the product needs to be serviced or repaired frequently, then ease of maintenance is crucial. For example, a user should be able to clear a paper jam in a printer or photocopier easily. Again, it is critical that the features of the product communicate maintenance/repair procedures to the user. However, in many cases, a more desirable solution is to eliminate the need for maintenance entirely.
- ***How many user interactions are required for the product's functions?*** In general, the more interactions users have with the product, the more the product will depend on ID. For example, a doorknob typically requires only one interaction, whereas a laptop computer may require a dozen or more, all of which the industrial designer must understand in depth. Furthermore, each interaction may require a different design approach and/or additional research.

- ***How novel are the user interaction needs?*** A user interface requiring incremental improvements to an existing design will be relatively straightforward to design, such as the buttons on a new desktop computer mouse. A more novel user interface may require substantial research and feasibility studies, such as the "click wheel" on the early Apple iPod music player.
- ***What are the safety issues?*** All products have safety considerations. For some products, these can present significant challenges to the design team. For example, the safety concerns in the design of a child's toy are much more prominent than those for a new computer mouse.

Aesthetic Needs

- ***Is visual product differentiation required?*** Products with stable markets and technology are highly dependent upon ID to create aesthetic appeal and, hence, visual differentiation. In contrast, a product such as a computer's internal disk drive, which is differentiated by its technological performance, is less dependent on ID.
- ***How important are pride of ownership, image, and fashion?*** A customer's perception of a product is in part based upon its aesthetic appeal. An attractive product may be associated with high fashion and image and will likely create a strong sense of pride among its owners. This may similarly be true for a product that looks and feels rugged or conservative. When such characteristics are important, ID will play a critical role in determining the product's ultimate success.
- ***Will an aesthetic product motivate the team?*** A product that is aesthetically appealing can generate a sense of team pride among the design and manufacturing staff. Team pride helps motivate and unify everyone associated with the project. An early ID concept gives the team a concrete vision of the end result of the development effort.

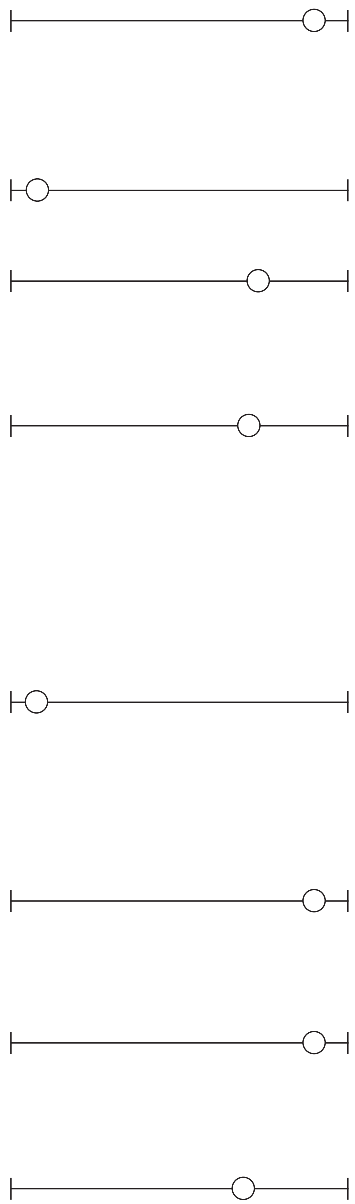
To demonstrate this method, we can use the above questions to assess the importance of industrial design in the development of the Motorola RAZR phone. Exhibit 11-3 displays the results of such analysis. We find that both ergonomics and aesthetics were extremely important for the RAZR. Accordingly, ID did indeed play a large role in determining many of the product's critical success factors.

The Impact of Industrial Design

The previous section focused primarily upon the importance of ID in satisfying customer needs. Next we explore both the direct economic impact of investing in ID as well as its impact on corporate identity.

Is Industrial Design Worth the Investment?

Managers will often want to know, for a specific product or for a business operation in general, how much effort should be invested in industrial design. While it is difficult to answer this question precisely, we can offer several insights by considering the costs and benefits. The costs of ID include direct cost, manufacturing cost, and time cost, described next.



Needs	Level of Importance (Low – Medium – High)	Explanation of Rating
Ergonomics		
Ease of use		Critical for a mobile telephone because it may be used frequently, may be needed in emergency situations, and can be operated by motorists while driving. The product's function must be communicated through its design.
Ease of maintenance		As with many integrated electronics products there is very little maintenance required.
Quantity of user interactions		There are many important user interactions such as entering text, dialing and storing numbers, sending and receiving calls, taking photos, Internet access.
Novelty of user interactions		Design solutions associated with some of the customer interactions were straightforward, such as the numeric keypad, because there is a wealth of human factors data that dictate the basic dimensions. However, other interfaces, such as the one-handed operation of such a thin phone, were quite different from earlier models and therefore required careful study.
Safety		There were few safety issues for ID to consider on the RAZR itself. However, because many customers use mobile telephones in automobiles, a line of Bluetooth wireless accessories needed to be designed for safe, convenient, hands-free operation.
Aesthetics		
Product differentiation		There were hundreds of models of mobile phones on the market when the RAZR was introduced. Its appearance was essential for differentiation.
Pride of ownership, fashion, or image		The RAZR was intended to be a highly visible product used by people for business and personal communication in public areas. It had to be stunningly attractive in everyday use.
Team motivation		The RAZR's novel form turned out to be an important inspiration to the development team and a selling point for senior management.

EXHIBIT 11-3 Assessing the importance of industrial design for Motorola's RAZR mobile phone.

- *Direct cost* is the cost of the ID services. This quantity is determined by the number and type of designers used, duration of the project, and number of models required, plus material costs and other related expenses. In 2011, ID consulting services in the United States cost $75 to $300 per hour, with most of the work being done by junior-level designers in the lower half of this price range and senior designers contributing relatively few hours of more strategic work in the higher half of the range. Additional charges include costs for models, photos, and other expenses. The true cost of internal corporate design services is generally about the same.
- *Manufacturing cost* is the expense incurred to implement the product details created through ID. Surface finishes, stylized shapes, rich colors, and many other design details can increase tooling cost and/or production cost. Note, however, that many ID details can be implemented at practically no cost, particularly if ID is involved early enough in the process (see below). In fact, some ID inputs can actually reduce manufacturing costs—particularly when the industrial designer works closely with the manufacturing engineers.
- *Time cost* is the penalty associated with extended lead time. As industrial designers attempt to refine the ergonomics and aesthetics of a product, multiple design iterations and/or prototypes will be necessary. This may result in a delay in the product's introduction, which will likely have an economic cost.

The benefits of using ID include increased product appeal and greater customer satisfaction through additional or better features, strong brand identity, and product differentiation. These benefits usually translate into a price premium and/or increased market share (as compared to marketing the product without the ID efforts).

These costs and benefits of ID were estimated as part of a study conducted at MIT that assessed the impact of detail design decisions on product success factors for a set of competing products in the market (automatic drip coffeemakers). Although the relation is difficult to quantify precisely, this study found a significant correlation between product aesthetics (as rated by practicing industrial designers) and the retail price for each product, but no correlation between aesthetics and manufacturing cost. The researchers could not conclude whether the manufacturers had priced their products optimally and could not determine unequivocally if aesthetics of the products enabled manufacturers to garner higher prices. However, the study suggests that an increase in price of $1 per unit for typical sales volumes would be worth several million dollars in profits over the life of these products. Industrial designers asked to price design services for such products gave a range from $75,000 to $250,000, suggesting that if ID could add even one dollar's worth of perceived benefit to the consumer, it would pay back handsomely (Pearson, 1992).

A second study, conducted at the Open University in England, also suggests that investing in ID yields a positive return. This study tracked the commercial impact of investing in engineering and ID for 221 design projects at small and medium-sized manufacturing firms. The study found that investing in industrial design consultants led to profits in over 90 percent of all implemented projects, and when comparisons were possible with previous, less ID-oriented products, sales increased by an average of 41 percent (Roy and Potter, 1993). More recent studies have assessed ID effectiveness and the integration of ID into the product development process and found positive correlations between these ID measures and corporate financial performance (Gemser and Leenders, 2001; Hertenstein et al., 2005).

For a specific project decision, performing simple calculations and sensitivity analyses can help quantify the likely economic returns from ID. For example, if investing in ID will likely result in a price premium of $10 per unit, what will be the net economic benefit when summed over the original market sales projections? Similarly, if investing in ID will likely result in a greater demand for the product—by, say, 1,000 units per year—what will be the net economic benefit when summed at the original unit price? The rough estimates of these benefits can be compared to the expected cost of the ID effort. Spreadsheet models are commonly used for this kind of financial decision making and can easily be applied to estimate the expected payback of ID for a project. (Chapter 17, Product Development Economics, describes a method for developing such a financial model.)

How Does Industrial Design Establish a Corporate Identity?

Corporate identity is derived from "the visual style of an organization," a factor that affects the firm's positioning in the market (Olins, 1989). A company's identity emerges primarily through what people see. Advertising, logos, signage, uniforms, buildings, packaging, and product designs all contribute to creating corporate identity.

In product-based companies, ID plays an important role in determining the company's identity. Industrial design determines a product's style, which is directly related to the public perception of the firm. When a company's products maintain a consistent and recognizable appearance, *visual equity* is established. A consistent look and feel may be associated with the product's color, form, style, or even its features. When a firm enjoys a positive reputation, such visual equity is valuable, as it can create a positive association with quality for future products. Some companies that have effectively used ID to establish visual equity and corporate identity through their product lines include:

- ***Apple Inc.:*** The original Macintosh had a small, upright shape and a benign buff coloring. This design purposely gave the product a nonthreatening, user-friendly look that has since been associated with all of Apple's products. More recent Apple designs have striking lines and innovative styling in silver, black, and white finishes.
- ***Rolex Watch Co.:*** The Rolex line of watches maintains a classic look and solid feel that signifies quality and prestige.
- ***Braun GmbH:*** Braun kitchen appliances and shavers have clean lines and basic colors. The Braun name has long been associated with simplicity and quality.
- ***Bang & Olufsen a/s:*** B&O high-fidelity consumer electronics systems are designed to have sleek lines and impressive visual displays, providing an image of technological innovation.
- ***BMW AG:*** BMW automobiles, known for luxury features and driver-oriented performance, display exterior styling features that have evolved slowly, retaining the equity associated with the brand.
- ***Motorola, Inc.:*** The original MicroTAC and StarTAC mobile phones were recognized as Motorola's leading-edge flip-phone innovations. The later RAZR model also used a folding clamshell concept in a much thinner form factor, emphasizing Motorola's leadership in a rapidly evolving industry.

The Industrial Design Process

Many large companies have internal industrial design departments. Small companies tend to use contract ID services provided by consulting firms. In either case, industrial designers should participate fully on cross-functional product development teams. Within these teams, engineers will generally follow a process to generate and evaluate concepts for the technical features of a product. In a similar manner, most industrial designers follow a process for designing the aesthetics and ergonomics of a product. Although this approach may vary depending on the firm and the nature of the project, industrial designers also generate multiple concepts and then work with engineers to narrow these options down through a series of evaluation steps.

Specifically, the ID process can be thought of as consisting of the following phases:

1. Investigation of customer needs.
2. Conceptualization.
3. Preliminary refinement.
4. Further refinement and final concept selection.
5. Control drawings or models.
6. Coordination with engineering, manufacturing, and external vendors.

This section discusses each of these phases in order, and the following section will discuss the timing of these phases within the overall product development process.

1. Investigation of Customer Needs

The product development team begins by documenting customer needs as described in Chapter 5, Identifying Customer Needs. Because industrial designers are skilled at recognizing issues involving user interactions, ID involvement is crucial in the needs process. For example, in researching customer needs for a new medical instrument, the team would study an operating room, interview physicians, and conduct focus groups. While involvement of marketing, engineering, and ID certainly leads to a common, comprehensive understanding of customer needs for the whole team, it particularly allows the industrial designer to gain an intimate understanding of the interactions between the user and the product.

Unlike many development efforts, the RAZR project did not rely heavily upon focus groups or formal market research. Motorola believed that the high level of secrecy surrounding the project, and the difficulty in gaining customer input for next-generation products, made these techniques impractical. Instead, the team used extensive input from Motorola employees to understand the evolution of user needs. Marketing personnel stressed the importance of Motorola's leadership in form factor and style. Engineering supplied information on technical limitations involving materials and geometry of components. Motorola's research on consumer perceptions of quality in mobile phones revealed that while light weight was desirable, the phone's density was also critical, resulting in a target specification for overall density.

2. Conceptualization

Once the customer needs and constraints are understood, the industrial designers help the team conceptualize the product. During the concept generation stage engineers naturally focus their attention upon finding solutions to the technical subfunctions of the product. (See Chapter 7, Concept Generation.) At this time, the industrial designers concentrate upon creating the product's form and user interfaces. Industrial designers make simple sketches, known as *thumbnail sketches,* of each concept. These sketches are a fast and inexpensive medium for expressing ideas and evaluating possibilities. Exhibit 11-4 shows two such sketches from the RAZR project.

The proposed concepts may then be matched and combined with the technical solutions under exploration. Concepts are grouped and evaluated by the team according to the customer needs, technical feasibility, cost, and manufacturing considerations. (See Chapter 8, Concept Selection.)

It is unfortunate that in some companies, industrial designers work quite independently from engineering. When this happens, ID is likely to propose concepts involving strictly form and style, and there are usually numerous iterations when engineering finds the concepts technically infeasible. Firms have therefore found it beneficial to tightly coordinate the efforts of industrial designers and engineers throughout the concept development phase so that these iterations can be accomplished more quickly—even in sketch form.

3. Preliminary Refinement

In the preliminary refinement phase, industrial designers build models of the most promising concepts. *Soft models* are typically made in full scale using foam or foam-core board. They are the second-fastest method—only slightly slower than sketches—used to evaluate concepts.

Although generally quite rough, these models are invaluable because they allow the development team to express and visualize product concepts in three dimensions. Concepts are evaluated by industrial designers, engineers, marketing personnel, and (at times) potential customers through the process of touching, feeling, and modifying the models. Typically, designers will build as many models as possible depending on time and financial constraints. Concepts that are particularly difficult to visualize require more models than do simpler ones.

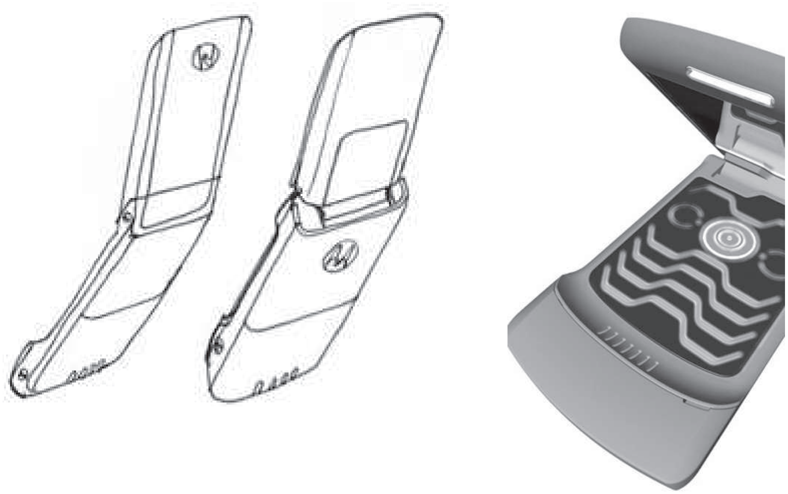
The RAZR industrial designers used numerous soft models to assess the overall size, proportion, and shape of many proposed concepts. Of particular concern was the feel of the product in the hand and against the face. These attributes can only be assessed using physical models. A soft model from the RAZR project, made using rapid prototyping technology, is shown in Exhibit 11-5.

4. Further Refinement and Final Concept Selection

At this stage, industrial designers often switch from soft models and sketches to hard models and information-intensive drawings known as *renderings*. Renderings show the details of the design and often depict the product in use. Drawn in two or three dimensions, they convey a great deal of information about the product. Renderings are often used for color studies and for testing customers' reception to the proposed product's features and functionality. A rendering from the RAZR project is shown in Exhibit 11-4.

The final refinement step before selecting a concept is to create *hard models*. These models are still technically nonfunctional yet are close replicas of the final design with a very realistic look and feel. They are made from wood, dense foam, plastic, or metal; are painted and textured; and have some "working" features such as buttons that push or

EXHIBIT 11-4
Two quick thumbnail concept sketches (left) and a more detailed colored rendering (right) showing evolution of the RAZR concept.



Courtesy of Motorola Inc.

sliders that move. Because a hard model can cost thousands of dollars, a product development team usually has the budget to make only a few.

For many types of products, hard models are fabricated to have the intended size, density, weight distribution, surface finish, and color. Hard models can then be used by industrial designers and engineers to further refine the final concept specifications. Furthermore, these models can also be used to gain additional customer feedback in focus groups, to advertise and promote the product at trade shows, and to sell the concept to senior management within an organization.

Exhibit 11-5 shows one of the several hard models built during the RAZR development process. Extensive usability testing was begun with the RAZR hard models. Tests identified the need for larger keypad buttons on a thinner phone. Designers also realized the need to locate the volume control buttons on the side of the display housing for easier

EXHIBIT 11-5
A soft model (left) and a hard model (right) used by the RAZR industrial designers to study alternative forms.

Courtesy of Motorola Inc.

access when open, rather than on the side of the keypad housing. They also found that this location required reversal of the +/− functionality of these buttons when the flip is opened.

5. Control Drawings or Models

Industrial designers complete their development process by making *control drawings* or *control models* of the final concept. Control drawings or models document functionality, features, sizes, colors, surface finishes, and key dimensions. Although they are not detailed part drawings (known as engineering drawings), they can be used to fabricate final design models and other prototypes. Typically, these drawings or models are given to the engineering team for detailed design of the parts. Exhibit 11-6 shows one view of the control model of the final RAZR design.

6. Coordination with Engineering, Manufacturing, and External Vendors

The industrial designers must continue to work closely with engineering and manufacturing personnel throughout the subsequent product development process. Some industrial design consulting firms offer quite comprehensive product development services, including detailed engineering design and the selection and management of outside vendors of materials, tooling, components, and assembly services.

The Impact of Computer-Based Tools on the ID Process

Since the 1990s, computer-aided design (CAD) tools have had a significant impact on industrial designers and their work. Using modern 3D CAD tools, industrial designers can generate, display, and rapidly modify three-dimensional designs on high-resolution computer displays. In this manner, ID can potentially generate a greater number of detailed concepts more quickly, which may lead to more innovative design solutions. The visual realism of 3D CAD images can enhance communication within the product development team and eliminate much of the inaccuracy of the manually generated sketches historically provided by industrial designers (Cardaci, 1992). Furthermore, 3D CAD systems may be used to generate control models or drawings, and these data can be directly transferred to engineering design systems, allowing the entire development process to be more easily integrated. Exhibit 11-7 shows a 3D CAD model of the RAZR.

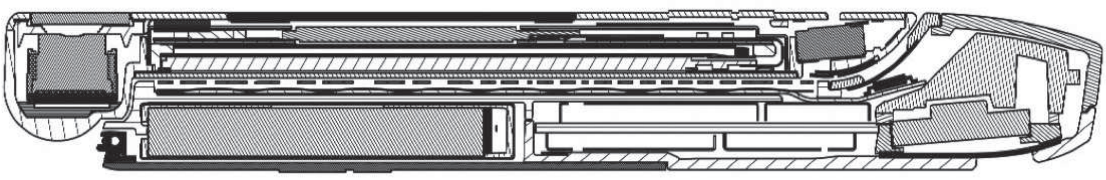
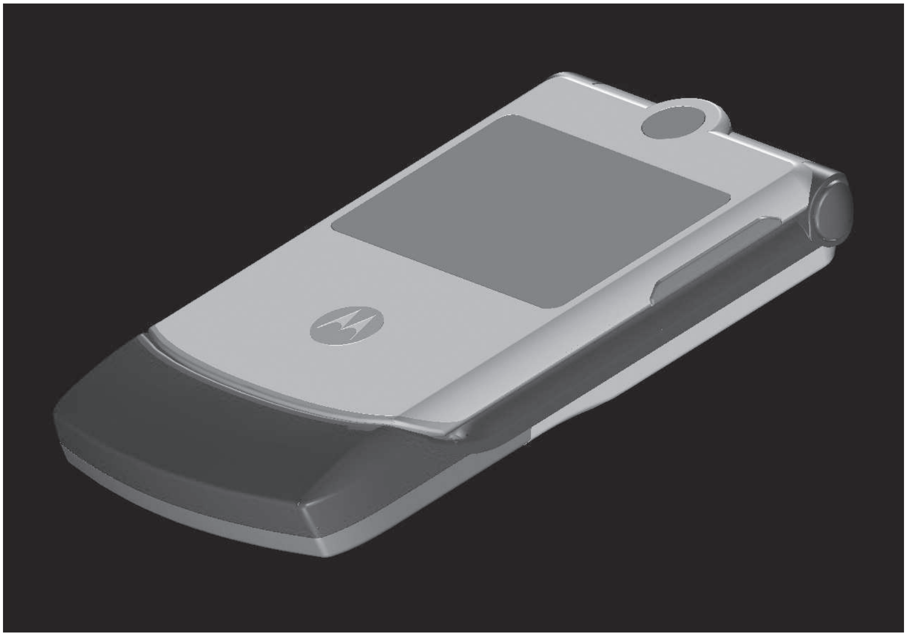


EXHIBIT 11-6 Side view of the RAZR control model defining the final RAZR shape and dimensions.



Courtesy of Motorola Inc.

EXHIBIT 11-7 3D CAD concept image created using Pro/ENGINEER software.

Management of the Industrial Design Process

Industrial design is typically involved in the overall product development process during several different phases. The timing of the ID effort depends upon the nature of the product being designed. To explain the timing of the ID effort it is convenient to classify products as technology-driven products and user-driven products.

- ***Technology-driven products:*** The primary characteristic of a technology-driven product is that its core benefit is based on its technology, or its ability to accomplish a specific technical task. While such a product may have important aesthetic or ergonomic requirements, consumers will most likely purchase the product primarily for its technical performance. For example, a hard disk drive for a computer is largely technology driven. It follows that for the development team of a technology-driven product, the engineering or technical requirements will be paramount and will dominate development efforts. Accordingly, the role of ID is often limited to packaging the core technology. This entails determining the product's external appearance and ensuring that the product communicates its technological capabilities and modes of interaction to the user.
- ***User-driven products:*** The core benefit of a user-driven product is derived from the functionality of its interface and/or its aesthetic appeal. Typically there is a high degree of user interaction for these products. Accordingly, the user interfaces must be safe, easy to use, and easy to maintain. The product's external appearance is often important to differentiate the product and to create pride of ownership. For example, an office

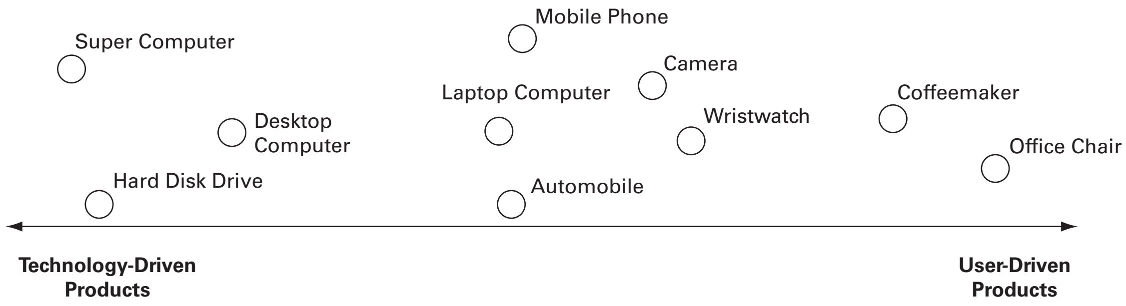


EXHIBIT 11-8 Classification of some common products on the continuum from technology-driven product to user-driven product.

chair is largely user driven. While these products may be technically sophisticated, the technology does not differentiate the product; thus, for the product development team, the ID considerations will be more important than the technical requirements. The role of engineering may still be important to determine any technical features of the product; however, since the technology is often already established, the development team focuses on the user aspects of the product.

Exhibit 11-8 classifies a variety of familiar products. Rarely does a product belong at one of the two extremes. Instead, most products fall somewhere along the continuum. These classifications can be dynamic. For example, when a company develops a product based on a new core technology, the company is often interested in bringing the product to market as quickly as possible. Because little emphasis is placed on how the product looks or is used, the initial role of ID is small. However, as competitors enter the market, the product may need to compete more along user or aesthetic dimensions. The product's original classification shifts, and ID assumes an extremely important role in the development process. One classic example is the Apple MacBook laptop computer. The core benefit of the first Apple laptop was its technology (a highly portable computer using the Macintosh operating system). As competition entered this market, however, Apple relied heavily on ID to create aesthetic appeal and enhanced utility, adding to the technical advantages of subsequent models.

Timing of Industrial Design Involvement

Typically, ID is incorporated into the product development process during the later phases for a technology-driven product and throughout the entire product development process for a user-driven product. Exhibit 11-9 illustrates these timing differences. Note that the ID process is a subprocess of the product development process; it is parallel but not separate. As shown in the exhibit, the ID process described above may be rapid relative to the overall development process. The technical nature of the problems that confront engineers in their design activities typically demands substantially more development effort than do the issues considered by ID.

Exhibit 11-9 shows that for a technology-driven product, ID activities may begin fairly late in the program. This is because ID for such products is focused primarily on packaging issues. For a user-driven product, ID is involved much more fully. In fact, the ID process may dominate the overall product development process for many user-driven products.

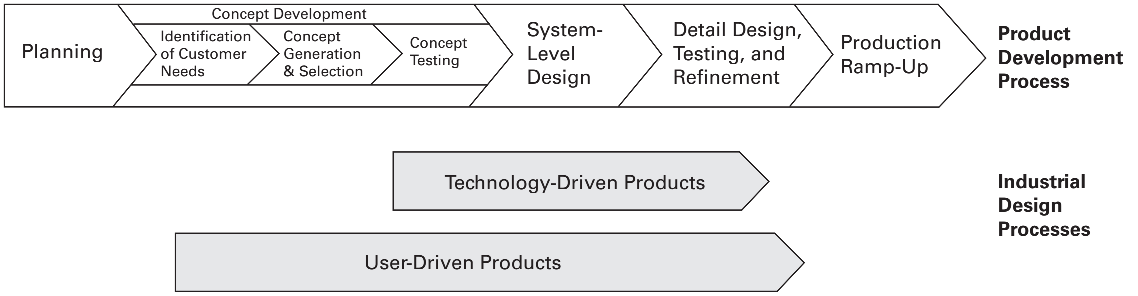


EXHIBIT 11-9 Relative timing of the industrial design process for two types of products.

Exhibit 11-10 describes the responsibilities of ID during each phase of the product development process and how they relate to the other activities of the development team. As with the timing of ID involvement, the responsibilities of ID may also change according to product type.

Product Development Activity	Type of Product	
	Technology-Driven	**User-Driven**
Identification of Customer Needs	ID typically has no involvement.	ID works closely with marketing to identify customer needs. Industrial designers participate in focus groups or one-on-one customer interviews.
Concept Generation and Selection	ID works with marketing and engineering to ensure that human factors and user-interface issues are addressed. Safety and maintenance issues are often of primary importance.	ID generates multiple concepts according to the industrial design process flow described earlier.
Concept Testing	ID helps engineering to create prototypes, which are shown to customers for feedback.	ID leads in the creation of models to be tested with customers by marketing.
System-Level Design	ID typically has little involvement.	ID narrows down the concepts and refines the most promising approaches.
Detail Design, Testing, and Refinement	ID is responsible for packaging the product once most of the engineering details have been addressed. ID receives product specifications and constraints from engineering and marketing.	ID selects a final concept, then coordinates with engineering, manufacturing, and marketing to finalize the design.

EXHIBIT 11-10 The role of industrial design according to product type.

Assessing the Quality of Industrial Design

Assessing the quality of ID for a finished product is an inherently subjective task. However, we can qualitatively determine whether ID has accomplished its goals by considering each aspect of the product that is influenced by ID. Below are five categories for evaluating a product. These categories roughly match Dreyfuss's five critical goals for ID, presented earlier in this chapter. We use these categories to develop specific questions, allowing the product to be rated along five dimensions. Exhibit 11-11 demonstrates this method by showing results for the RAZR.

1. Quality of the User Interface

This is a rating of how easy the product is to use. Interface quality is related to the product's appearance, feel, and modes of interaction.

- Do the features of the product effectively communicate their operation to the user?
- Is the product's use intuitive?
- Are all features safe?
- Have all potential users and uses of the product been considered?

Examples of product-specific questions include:

- Is the grip comfortable?
- Does the control knob turn easily and smoothly?
- Is the power switch easy to locate?
- Is the display easy to read and understand?

2. Emotional Appeal

This is a rating of the overall consumer appeal of the product. Appeal is achieved in part through appearance, feel, sound, and smell.

- Is the product attractive? Is it exciting?
- Does the product express quality?
- What images come to mind when viewing it?
- Does the product inspire pride of ownership?
- Does the product evoke feelings of pride among the development team and sales staff?

Examples of product-specific questions include:

- How does the car door sound when slammed?
- Does the hand tool feel solid and sturdy?
- Does the appliance look good on the kitchen counter?

3. Ability to Maintain and Repair the Product

This is a rating of the ease of product maintenance and repair. Maintenance and repair should be considered along with the other user interactions.

Assessment Category	Performance Rating (Low — Medium — High)	Explanation of Rating
1. Quality of the User Interface		In general, the RAZR was both easy to use and comfortable. Calls could be answered by simply opening the display, numbers and text could be easily entered using the keypad, and the functions were readily accessible using the navigation buttons. The RAZR's drawbacks included a keypad that could be difficult to use for customers with large fingers or long fingernails. In some markets, carriers had specified that Motorola customize the software interface in ways that negatively impacted usability.
2. Emotional Appeal		The RAZR had a high emotional appeal that stemmed from its ultra-thin form, pocketability, and finishes.
3. Ability to Maintain and Repair the Product		Although maintenance and repair were not of primary importance to the customer, the RAZR rated high in this category. The battery charged very quickly and could be removed and replaced easily.
4. Appropriate Use of Resources		The final design included only those features that satisfied real customer needs. Materials were selected for durability and manufacturability, to withstand extreme conditions, to meet environmental regulations, and to create an attractive appearance.
5. Product Differentiation		The RAZR's appearance was clearly unique. It was easily identified when viewed in a public area or next to a competitor's product.

EXHIBIT 11-11 Assessment of industrial design's role in the RAZR development project.

- Is the maintenance of the product obvious? Is it easy?
- Do product features effectively communicate disassembly and assembly procedures?

Examples of product-specific questions include:

- How easy and obvious is it to clear a paper jam in the printer?
- How difficult is it to disassemble and clean the food processor?
- How long does it take to change the batteries in the remote controller?

4. Appropriate Use of Resources

This is a rating of how well resources were used in satisfying the customer needs. Resources typically refer to the dollar expenditures on ID and other functions. These factors tend to drive costs such as manufacturing. A poorly designed product, one with unnecessary features, or a product made from an exotic material will affect tooling, manufacturing processes, assembly processes, and the like. This category asks whether these investments were well spent.

- How well were resources used to satisfy the customer requirements?
- Is the material selection appropriate (in terms of cost and quality)?
- Is the product over- or underdesigned (does it have features that are unnecessary or neglected)?
- Were environmental/ecological factors considered?

5. Product Differentiation

This is a rating of a product's uniqueness and consistency with the corporate identity. This differentiation arises predominantly from appearance.

- Will a customer who sees the product in a store be able to identify it because of its appearance?
- Will it be remembered by a consumer who has seen it in an advertisement?
- Will it be recognized when seen on the street?
- Does the product fit with or enhance the corporate identity?

From an ID perspective, as shown in Exhibit 11-11, the RAZR was an excellent product. It was novel, recognizable, durable, easy to fabricate, and had strong customer appeal. Since these features were extremely important to the consumer, ID played a critical role in determining the immediate market success of the product.

Summary

This chapter introduces the topic of industrial design, explains its benefits to product quality, and illustrates how the ID process takes place.

- The primary mission of ID is to design the aspects of a product that relate to the user: aesthetics and ergonomics.
- Most products can benefit in some way or another from ID. The more a product is seen or used by people, the more it will depend on good ID for its success.
- For products that are characterized by a high degree of user interaction and the need for aesthetic appeal, ID should be involved throughout the product development process. Early involvement of industrial designers will ensure that critical aesthetic and user requirements will not be overlooked or ignored by the technical staff.
- When a product's success relies more on technology, ID can be integrated into the development process later.
- Active involvement of ID on the product development team can help to promote good communication between functional groups. Such communication facilitates coordination and ultimately translates into higher-quality products.

References and Bibliography

Many current resources are available on the Internet via
www.ulrich-eppinger.net

For more information about industrial design—its history, impact, future, and practice—the following books and articles are recommended. The brief history of ID presented in this chapter was adapted from Lorenz's book.

Caplan, Ralph, *By Design*: *Why There Are No Locks on the Bathroom Doors in the Hotel Louis XIV, and Other Object Lessons,* St. Martin's Press, New York, 1982.

Dreyfuss, Henry, "The Industrial Designer and the Businessman," *Harvard Business Review,* November 1950, pp. 77–85.

Dreyfuss, Henry, *Designing for People,* Paragraphic Books, New York, 1967.

Harkins, Jack, "The Role of Industrial Design in Developing Medical Devices," *Medical Device and Diagnostic Industry,* September 1992, pp. 51–54, 94–97.

Lorenz, Christopher, *The Design Dimension: Product Strategy and the Challenge of Global Marketing,* Basil Blackwell, Oxford, UK, 1986.

Lucie-Smith, Edward, *A History of Industrial Design,* Van Nostrand Reinhold, New York, 1983.

Norman discusses good and bad examples of product design across a range of consumer products and provides principles and guidelines for good design practice. In *Emotional Design,* he explains how people connect with and react to the products they buy and use.

Norman, Donald A., *The Design of Everyday Things,* Doubleday, New York, 1990.

Norman, Donald A., *Emotional Design: Why We Love (or Hate) Everyday Things,* Basic Books, New York, 2004.

Boatwright and Cagan argue that many successful products are designed to connect with customers through strong, positive emotions.

Boatwright, Peter, and Jonathan Cagan, *Built to Love: Creating Products That Captivate Customers,* Berrett-Koehler, San Francisco, 2010.

Computer-aided industrial design (CAID), introduced in this article by Cardaci, has become an important part of ID practice today, replacing traditional rendering in many situations.

Cardaci, Kitty, "CAID: A Tool for the Flexible Organization," *Design Management Journal,* Design Management Institute, Boston, Vol. 3, No. 2, Spring 1992, pp. 72–75.

The following studies are among the very few that have critically assessed the value of ID to products and their manufacturers. A 1994 issue of *Design Management Journal* and a 2005 issue of *Journal of Product Innovation Management* were devoted to this topic.

Design Management Journal, Vol. 5, No. 2, Spring 1994.

Gemser, Gerda, and Mark A. A. M. Leenders, "How Integrating Industrial Design in the Product Development Process Impacts on Company Performance," *Journal of Product Innovation Management,* Vol. 18, No. 1, January 2001, pp. 28–38.

Hertenstein, Julie H., Marjorie B. Platt, and Robert W. Veryzer, "The Impact of Industrial Design Effectiveness on Corporate Financial Performance," *Journal of Product Innovation Management,* Vol. 22, No. 1, January 2005, pp. 3–21.

Journal of Product Innovation Management, Vol. 22, No. 1, January 2005.

Pearson, Scott, “Using Product Archaeology to Understand the Dimensions of Design Decision Making,” S. M. Thesis, MIT Sloan School of Management, May 1992.

Roy, Robin, and Stephen Potter, “The Commercial Impacts of Investment in Design,” *Design Studies,* Vol. 14, No. 2, April 1993, pp. 171–193.

Olins describes how a firm develops a corporate identity through design and communication.

Olins, Wally, *Corporate Identity: Making Business Strategy Visible through Design,* Harvard Business School Press, Boston, 1989.

Several excellent case studies involving the ID process and product development issues surrounding ID have been written by the Design Management Institute. Also the publications @ *Issue* (semiannually), *Innovation* (quarterly), and *I.D.* (bimonthly) include case studies, examples, and discussion of ID practices.

@ *Issue: The Journal of Business and Design,* Corporate Design Foundation, Boston.

Design Management Institute, Boston, www.dmi.org.

I.D. Magazine, F+W Publications, Inc., New York.

Innovation, Industrial Designers Society of America, Dulles, VA.

While industrial designers are best found through personal referral, IDSA publishes a list of ID firms and consultants.

Industrial Designers Society of America, Dulles, VA, www.idsa.org.

Exercises

1. Visit a local specialty store (e.g., kitchen supplies, tools, office supply, gifts) and photograph (or purchase) a set of competing products. Assess each one in terms of the five ID quality categories as shown in Exhibit 11-11. Which product would you purchase? Would you be willing to pay more for it than for the others?
2. Develop several concept sketches for a common product. Try designing the product form both “from the inside out” and “from the outside in.” Which is easier for you? Possible simple products include a stapler, a garlic press, an alarm clock, a reading light, and a telephone.
3. List some firms that you feel have a strong corporate identity. What aspects of their products helped to develop this identity?

Thought Questions

1. By what cause-and-effect mechanism does ID affect a product’s manufacturing cost? Under what conditions would ID increase or decrease manufacturing cost?
2. What types of products might not benefit from ID involvement in the development process?
3. The term *visual equity* is sometimes used to refer to the value of the distinctive appearance of a firm’s products. How is such equity obtained? Can it be “purchased” over a short time period, or does it accrue slowly?

Design for Environment

Courtesy of Herman Miller, Inc.

EXHIBIT 12-1 Three chairs in Herman Miller's line of office seating products. Shown (from left to right) are the Aeron (1994), Mirra (2004), and Setu (2009).

In June 2009, Herman Miller, Inc., a U.S.-based office furniture manufacturer, launched the Setu multipurpose chair. The Setu (named after the Hindi word for bridge) aims to set new standards of simplicity, adaptability, and comfort for multipurpose seating while being environmentally friendly. The Setu chair is one product in a very successful line of office seating, including also the Aeron and Mirra chairs shown in Exhibit 12-1.

Herman Miller designed the Setu chair in collaboration with Studio 7.5, a design firm based in Germany. Multipurpose chairs, such as the Setu, are used where people sit for relatively short periods, such as conference rooms, temporary workstations, and collaborative spaces. (This is in contrast to a task chair in which the user sits for longer periods.) Studio 7.5 found that many chairs in office spaces where people spend from a few minutes to a few hours at a time were uncomfortable and misadjusted. Moreover, most chairs are made with materials and processes that are harmful to the environment. Studio 7.5 recognized a market need for a new and innovative multipurpose chair—one combining comfort, design for environment, and a compelling price.

The core of Setu is a flexible spine, molded of two polypropylene materials and engineered to achieve comfort for nearly everybody (see Exhibit 12-2). As the user sits and reclines, the spine flexes, providing comfort and back support throughout the full range of tilt. Without any tilt mechanism and with only one adjustment (height), the chair is significantly lighter weight, less complex, and lower cost than the Aeron and Mirra task chairs.

The Setu chair emerged from Herman Miller's commitment to minimizing the environmental impacts of their products and operations, and provides a great example of how to incorporate environmental considerations into the product development process. The Setu is designed for material recycling and is produced using environmentally safe materials and renewable energy. The following factors explain its level of environmental performance:

- ***Environmentally friendly materials:*** The Setu multipurpose chair consists of environmentally safe and nontoxic materials such as 41 percent (by weight) aluminum, 41 percent polypropylene, and 18 percent steel.

EXHIBIT 12-2 The spine of the Setu chair is a combination of two polypropylene materials precisely engineered to flex and support as the user moves in the chair.

Courtesy of Herman Miller, Inc.

- ***Recycled content*: The Setu is made of 44 percent recycled materials (by weight, comprising 23 percent postconsumer and 21percent postindustrial recycled content).
- ***Recyclability:*** The Setu is 92 percent recyclable (by weight) at the end of its useful life. Steel and aluminum components are 100 percent recyclable. Polypropylene components are identified with a recycling code whenever possible to aid in returning these materials to the recycling stream. (Of course, recycling of industrial materials depends on the availability of such recycling streams.)
- ***Clean energy:*** Setu is manufactured on a production line that utilizes 100 percent green power (half from wind turbines and half from captured landfill off-gassing).
- ***Emissions:*** No harmful air or water emissions are released during Setu's production.
- ***Returnable and recyclable packaging:*** Setu components are received by Herman Miller from a network of nearby suppliers in molded tote trays that are returned to the suppliers for reuse. Outgoing packaging materials include corrugated cardboard and a polyethylene plastic bag, both materials capable of repeated recycling.

Design for environment (DFE) is a way to include environmental considerations in the product development process. This chapter presents a method for DFE, using the Herman Miller Setu chair as an example to illustrate the successful application of the DFE process.

What Is Design for Environment?

Every product has environmental impacts. DFE provides organizations with a practical method to minimize these impacts in an effort to create a more sustainable society. Just as effective design for manufacturing (DFM) practice has been shown to maintain or improve product quality while reducing costs (see Chapter 13, Design for Manufacturing), practitioners of DFE have also found that effective DFE practice can maintain or improve product quality and cost while reducing environmental impacts.

Environmental impacts of a product may include energy consumption, natural resource depletion, liquid discharges, gaseous emissions, and solid waste generation. These impacts fall into two broad categories—energy and materials—and both represent critical environmental problems that need to be solved. For most products, addressing the energy problem means developing products that use less energy and that use renewable energy. To address the materials problem is not as straightforward. Therefore, much of the focus of DFE in this chapter is on choosing the right materials for products and making sure they can be recycled.

During the early stages of the product development process, deliberate decisions about material use, energy efficiency, and waste avoidance can minimize or eliminate environmental impacts. However, once the design concept is established, improving environmental performance generally involves time-consuming design iterations. DFE therefore may involve activities throughout the product development process and requires an interdisciplinary approach. Industrial design, engineering, purchasing, and marketing all work together in the development of environmentally friendly products. In many cases product development professionals with specialized DFE training lead the DFE efforts within a project. However, all product development team members benefit from understanding the principles of DFE.

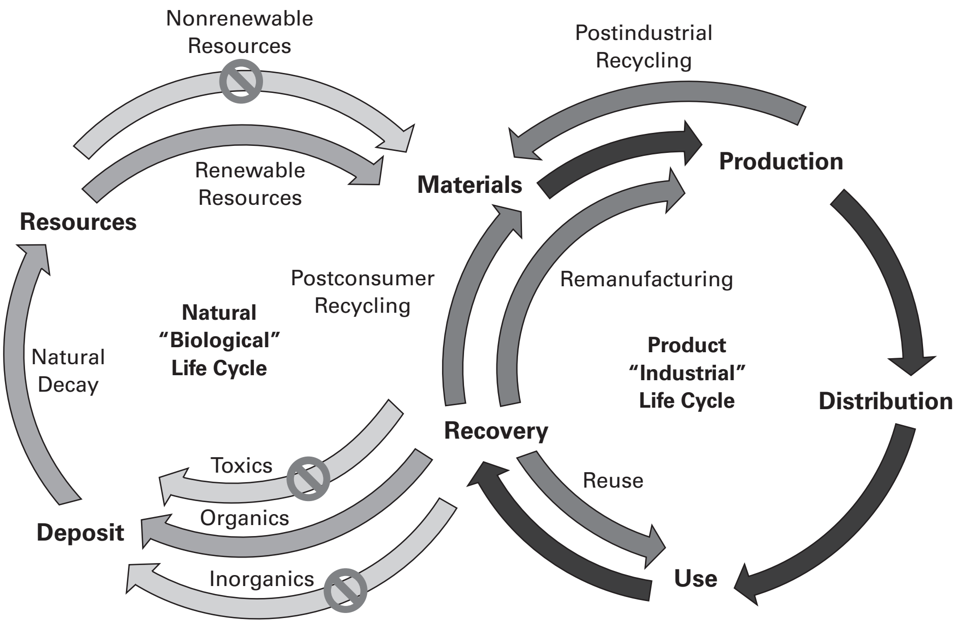
Two Life Cycles

Life cycle thinking is the basis of DFE. This helps to expand the traditional manufacturer's concern with the production and distribution of its products to comprise a closed-loop system relating the product life cycle to the natural life cycle, both of which are illustrated in Exhibit 12-3. The product life cycle begins with the extraction and processing of raw materials from natural resources, followed by production, distribution, and use of the product. Finally, at the end of the product's useful life there are several recovery options—remanufacturing or reuse of components, recycling of materials, or disposal through incineration or deposit in a landfill. The natural life cycle represents the growth and decay of organic materials in a continuous loop. The two life cycles intersect, as shown in the diagram, with the use of natural materials in industrial products and with the reintegration of organic materials back into the natural cycle.

While most product life cycles take place over a few months or years, the natural cycle spans a wider range of time periods. Most organic materials (plant- and animal-based) can decay relatively quickly and become nutrients for new growth of similar materials. However, other natural materials (such as minerals), are created on a much longer time scale, and so are considered to be nonrenewable natural resources. Therefore, depositing most mineral-based industrial materials into landfills does not readily re-create similar industrial materials for perhaps thousands of years (and often creating unnatural concentrations of certain harmful wastes).

Each of the product life cycle stages may consume energy and other resources and may generate emissions and waste, all of which have environmental impacts. From this life cycle perspective, in order to reach conditions of environmental sustainability, the materials in products must be balanced in a sustainable, closed-loop system. This gives rise to three challenges of product design to reach sustainability, which are also represented in the life cycle diagram of Exhibit 12-3.

EXHIBIT 12-3 The natural life cycle and the product life cycle.



1. Eliminate use of nonrenewable natural resources (including nonrenewable sources of energy).
2. Eliminate disposal of synthetic and inorganic materials that do not decay quickly.
3. Eliminate creation of toxic wastes that are not part of natural life cycles.

Organizations committed to DFE intend to work toward achieving these sustainability conditions over time. DFE helps these organizations to create better products by choosing materials carefully and by enabling proper recovery options so that the materials used in products can be reintegrated either into the product life cycle or into the natural life cycle.

Environmental Impacts

Every product may have a number of environmental impacts over its life cycle. The following list explains some of the environmental impacts deriving from the manufacturing sector (adapted from Lewis et al., 2001):

- ***Global warming:*** Scientific data and models show that the temperature of the earth is gradually increasing as a result of the accumulation of greenhouse gases, particulates, and water vapor in the upper atmosphere. This effect appears to be accelerating as a result of emissions of carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), black carbon particles, and nitrogen oxides (NO_x) from industrial processes and products.
- ***Resource depletion:*** Many of the raw materials used for production, such as iron ore, gas, oil, and coal, are nonrenewable and supplies are limited.
- ***Solid waste:*** Products may generate solid waste throughout their life cycle. Some of this waste is recycled, but most is disposed in incinerators or landfills. Incinerators generate air pollution and toxic ash (which goes into landfills). Landfills may also create concentrations of toxic substances, generate methane gas (CH_4), and release groundwater pollutants.
- ***Water pollution:*** The most common sources of water pollution are discharges from industrial processes, which may include heavy metals, fertilizers, solvents, oils, synthetic substances, acids, and suspended solids. Waterborne pollutants may affect groundwater, drinking water, and fragile ecosystems.
- ***Air pollution:*** Sources of air pollution include emissions from factories, power-generating plants, incinerators, residential and commercial buildings, and motor vehicles. Typical pollutants include CO_2, NO_x, sulfur dioxide (SO_2), ozone (O_3), and volatile organic compounds (VOCs).
- ***Land degradation:*** Land degradation concerns the adverse effects that raw material extraction and production, such as mining, farming, and forestry, have on the environment. The effects include reduced soil fertility, soil erosion, salinity of land and water, and deforestation.
- ***Biodiversity:*** Biodiversity concerns the variety of plant and animal species, and is affected by land clearing for urban development, mining, and other industrial activities.
- ***Ozone depletion:*** The ozone layer protects the earth against the harmful effects of the sun's radiation. It is degraded by reactions with nitric acid (created by the burning of fossil fuels) and chorine compounds (such as CFCs).

History of Design for Environment

The birth of DFE is often traced to the early 1970s. Papanek (1971) challenged designers to face their social and environmental responsibilities instead of only commercial interests. The World Commission on Environment and Development's *Brundtland Report* (1987) first defined the term *sustainable development* as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

In the 1990s, several influential books about environmentally friendly design were published. Burall (1991) argued that there was no longer a conflict between a green approach to design and business success. Fiksel (1996; revised 2009) discussed how DFE integrates life cycle thinking into new product and process development. As the DFE process matured, Brezet and van Hemel (1997) provided a practical guide called *Ecodesign*. Also in the 1990s the Technical University of Delft, Philips Electronics, and the Dutch government collaborated to develop a life cycle analysis software tool providing metrics to assess the overall environmental impact of a product.

Today's sustainable development movement embraces the broader concept of sustainable product design (Bhamra and Lofthouse, 2007), which includes not only DFE but also the social and ethical implications of products. Even though authors have used various terminology for environmentally friendly design approaches, the terms *green design, ecodesign, sustainable design,* and *DFE* are more or less synonymous today.

Herman Miller's Journey toward Design for Environment

Many manufacturing firms have begun to embrace DFE. However, few have done so to the extent of Herman Miller, where DFE is central to its corporate strategy. Herman Miller strives to maintain high product quality standards while incorporating increasingly more environmentally friendly materials, manufacturing processes, and product function into every new product design.

In 1999, Herman Miller formed a design for environment (DFE) team. This team is responsible for developing environmentally sensitive design standards for new and existing Herman Miller products. McDonough Braungart Design Chemistry (MBDC), a product and industrial process design firm based in Virginia, supports the DFE team in its mission. McDonough and Braungart (2002) stated in their book, *Cradle to Cradle: Remaking the Way We Make Things,* that the traditional DFE approach—designing products that are merely less harmful to the environment due to incremental improvements such as reduced energy use, waste generation, or use of toxic materials—is not sufficient because such products are still unhealthy for the environment. To advance from less harmful to truly environmentally friendly products, McDonough and Braungart introduced a DFE method that focuses on three key areas of product design:

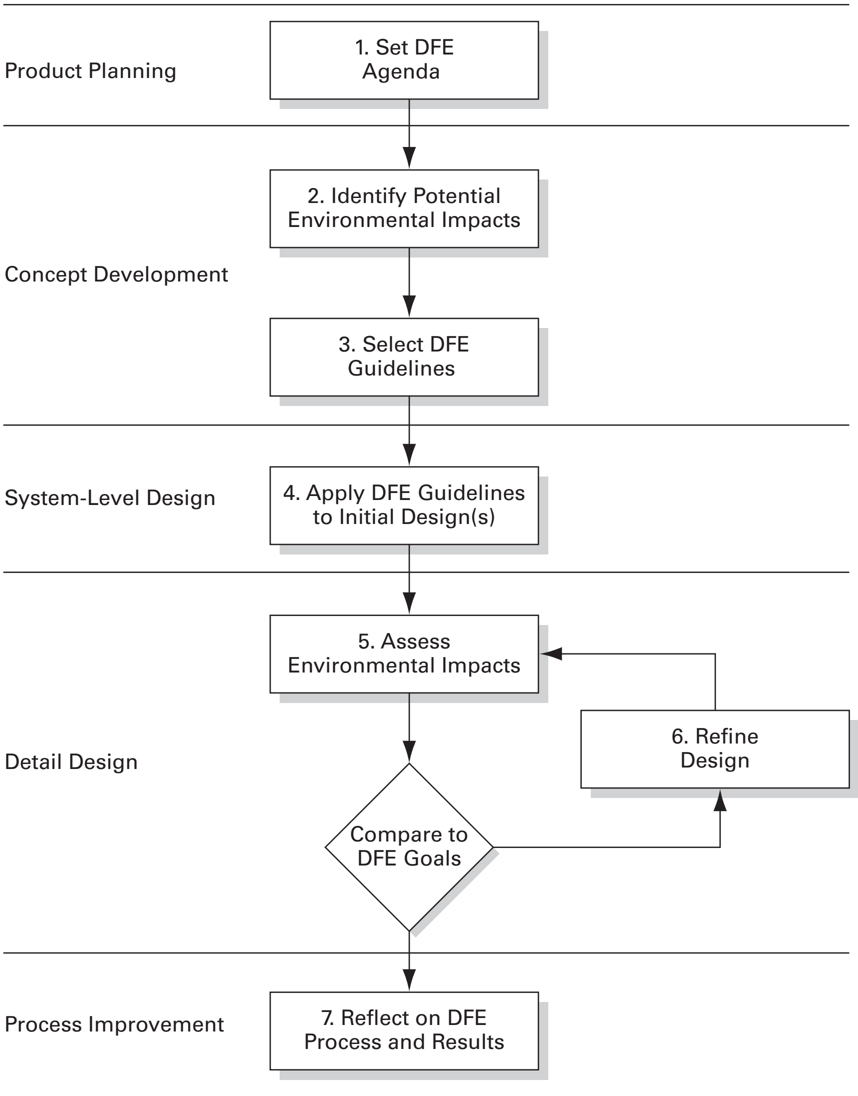
- ***Material chemistry:*** What chemicals comprise the specified materials? Are they safe for humans and the environment?
- ***Disassembly:*** Can the products be taken apart at the end of their useful life in order to recycle their materials?
- ***Recyclability:*** Do the materials contain recycled content? Are the materials readily separable into recycling categories? Can the materials be recycled at the end of the product's useful life?

To implement DFE, Herman Miller has built a team of DFE experts who work on every new product development team. With MBDC, they have created a materials database and a DFE assessment tool, which provide metrics to guide design decisions throughout the product development process.

The Design for Environment Process

Effective implementation of DFE includes activities throughout the product development process. The steps of the DFE process are shown in Exhibit 12-4. Despite the linear presentation of the steps, product development teams will likely repeat some steps several times, making DFE an iterative process. The following sections describe each step of the DFE process.

EXHIBIT 12-4 The DFE process involves activities throughout the product development process.



Step 1: Set the DFE Agenda: Drivers, Goals, and Team

The DFE process begins as early as the product planning phase with setting the DFE agenda. This step consists of three activities: identifying the internal and external drivers of DFE, setting the environmental goals for the product, and setting up the DFE team. By setting the DFE agenda, the organization identifies a clear and actionable path toward environmentally friendly product design.

Identify the Internal and External Drivers of DFE

The planning phase of DFE begins with a discussion of the reasons why the organization wishes to address the environmental performance of its products. It is useful to document both the internal drivers and the external drivers of DFE. This list may evolve over time, as changes in technology, regulation, experience, stakeholders, and competition each affect the capability and challenges of the organization.

Internal drivers are the DFE objectives within the organization. Typical internal drivers of DFE are (adapted from Brezet and van Hemel, 1997):

- ***Product quality:*** A focus on environmental performance may raise the quality of the product in terms of functionality, reliability in operation, durability, and repairability.
- ***Public image:*** Communicating a high level of environmental quality of a product can improve a company's image.
- ***Cost reduction:*** Using less material and less energy in production can result in considerable cost savings. Generating less waste and eliminating hazardous waste results in lower waste disposal costs.
- ***Innovation:*** Sustainable thinking can lead to radical changes in product design and may foster innovation across the whole company.
- ***Operational safety:*** By eliminating toxic materials, many DFE changes can help improve the occupational health and safety of employees.
- ***Employee motivation:*** Employees can be motivated to contribute in new and creative ways if they are able to help reduce the environmental impacts of the company's products and operations.
- ***Ethical responsibility:*** Interest in sustainable development among managers and product developers may be motivated in part by a moral sense of responsibility for conserving the environment and nature.
- ***Consumer behavior:*** Wider availability of products with positive environmental benefits may accelerate the transition to cleaner lifestyles and demand for greener products.

External drivers of DFE typically include environmental regulations, customer preferences, and the offerings of competitors, such as (from Brezet and van Hemel, 1997):

- ***Environmental legislation:*** Product-oriented environmental policy is developing rapidly. Companies must not only understand the myriad regulations in the various regions where they operate and sell products, but also be able to anticipate future legislation. The focus of recent legislation is shifting from the prohibition of certain materials to broader producer responsibility, including take-back obligations.

- ***Market demand:*** Today, companies operate in a business environment of increasingly well-informed industrial customers and end users who may demand sustainable products. Negative publicity, blogs, and boycotts of products, manufacturers, or retailers can have considerable impact on sales. Of course, the opposite positive effect is becoming more powerful as well.
- ***Competition:*** Sustainability activities undertaken by competitors can lead to pressure for more emphasis on DFE. Setting a high environmental standard may create a first-mover advantage.
- ***Trade organizations:*** Trade or industrial organizations in some branches of industry—such as packaging and automobile manufacturing—encourage companies to take environmental action by sharing technology and establishing codes of conduct.
- ***Suppliers:*** Suppliers influence company behavior by introducing more sustainable materials and processes. Companies may choose to audit and confirm environmental declarations of their suppliers.
- ***Social pressures:*** Through their social and community contacts, managers and employees may be asked about the responsibility that their business takes for the environment.

Key DFE drivers for the Setu chair were market demand, innovation, and Herman Miller's commitment to environmental responsibility. Studio 7.5 and Herman Miller developed the early Setu concepts with these drivers in mind.

Set the DFE Goals

An important activity in the product planning phase is to set the environmental goals for each product development project. Many organizations have established a strategy that includes long-term environmental goals. These goals define how the organization complies with environmental regulations and how the organization reduces the environmental impacts of its products, services, and operations.

In 2005, Herman Miller set its long-term environmental goals for the year 2020:

- Zero landfill.
- Zero hazardous waste generation.
- Zero harmful air emissions.
- Zero process water use.
- All green electrical energy use.
- All buildings certified to meet environmental efficiency standards.
- All sales from products created with the DFE process.

To achieve the long-term goals, specific environmental goals may be set for every product during the planning phase. These individual goals also allow the organization to make progress toward the long-term strategy. Exhibit 12-5 lists examples of DFE goals, arranged according to the product life cycle. Based on an understanding of which life cycle stages contribute significant environmental impacts, goals may be developed accordingly.

EXHIBIT 12-5
Example DFE goals, arranged according to the product life cycle stages. Adapted from Giudice et al. (2006).

Life Cycle Stage	Example Design for Environment Goals
Materials	• Reduce the use of raw materials. • Choose plentiful, renewable raw materials. • Eliminate toxic materials. • Increase the energy efficiency of material extraction processes. • Reduce discards and waste. • Increase the use of recovered and recycled materials.
Production	• Reduce the use of process materials. • Specify process materials that can be fully recovered and recycled. • Eliminate toxic process materials. • Select processes with high energy efficiency. • Reduce production scrap and waste.
Distribution	• Plan the most energy-efficient shipping. • Reduce emissions from transport. • Eliminate toxic and dangerous packaging materials. • Eliminate or reuse packaging.
Use	• Extend useful product life. • Promote use of products under the intended conditions. • Enable clean and efficient servicing operations. • Eliminate emissions and reduce energy consumption during use.
Recovery	• Facilitate product disassembly to separate materials. • Enable the recovery and remanufacturing of components. • Facilitate material recycling. • Reduce waste volume for incineration and landfill deposit.

Herman Miller understands that the primary environmental impacts of their office furniture products are in the materials, production, and recovery stages. For the Setu chair, Herman Miller aimed to use exclusively materials with low environmental impact, facilitate product disassembly, and enable recycling.

Set Up the DFE Team

DFE requires participation by many functional experts on the product development project. The typical composition of a DFE team (often a subteam within the overall project team) consists of a DFE leader, an environmental chemistry and materials expert, a manufacturing engineer, and a representative from the purchasing and supply chain organization. Of course, the DFE team composition depends on the organization and needs of the specific project, and may also include marketing professionals, outside consultants, suppliers, or other experts.

Herman Miller created their DFE team in 1999 to work with the designers and engineers on every product development project to review material chemistry, disassembly, recyclability, incoming and outgoing packaging, energy sources and uses, and waste generation. The DFE team is involved as early as possible to ensure that DFE considerations are taken into account right from the start. By working closely with each product development team, the DFE team provides the tools and knowledge for making environmentally sound design decisions.

Step 2: Identify Potential Environmental Impacts

Within the concept development phase, DFE begins by identifying the potential environmental impacts of the product over its life cycle. This enables the product development team to consider environmental impacts at the concept stage even though little or no specific data (regarding material and energy use, emissions, and waste generation) are yet available for the actual product and a detailed environmental impact assessment is not yet possible. In the case of product redesign, however, relevant data may be provided by impact analysis of some existing products. (See life cycle assessment methods in step 5 below.)

Exhibit 12-6 shows a chart that can be used to qualitatively assess the environmental impacts over the product life cycle. The chart is an adaption of the LiDS Wheel (Brezet and van Hemel, 1997) and the EcoDesign Web (Bhamra and Lofthouse, 2007). To create this chart, the team asks, "What are the significant sources of potential environmental impact in each life cycle stage?" Specific questions for each stage are given in Exhibit 12-7 and may be helpful in conducting this qualitative analysis.

The team lists for each life cycle stage the anticipated key environmental impacts. The height of each bar in the chart represents the team's judgment about the overall magnitude of the potential environmental impacts and therefore where to focus their DFE efforts. For some products (e.g. automobiles, electronic devices) the most significant impacts are found to be in the use stage. For other products (e.g. clothing, office furniture) the greatest impacts may be in the materials, production, and recovery stages. Exhibit 12-6 shows a qualitative life cycle assessment for office furniture in general. This understanding guided DFE in the Setu chair project.

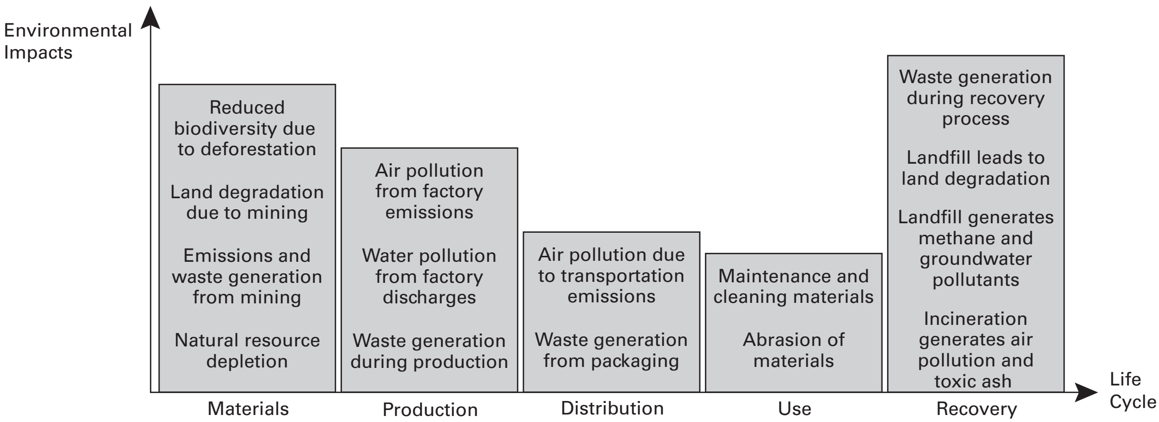


EXHIBIT 12-6 The qualitative life cycle assessment represents the team's estimate of the potential types and magnitudes of environmental impacts of the product over its life cycle. This chart depicts the types of impacts most relevant to office furniture products such as the Setu chair.

Life Cycle Stage	Questions
Materials	• How much, and what types of recyclable materials will be used? • How much, and what types of non recyclable materials will be used? • How much, and what types of additives will be used? • What is the environmental profile of the materials? • How much energy will be required to extract these materials? • Which means of transport will be used to procure them?
Production	• How many, and what types of production processes will be used? • How much, and what types of auxiliary materials are needed? • How high will the energy consumption be? • How much waste will be generated? • Can production waste be separated for recycling?
Distribution	• What kind of transport packaging, bulk packaging, and retail packaging will be used (volumes, weights, materials, reusability)? • Which means of transport will be used?
Use	• How much, and what type of energy will be required? • How much, and what kind of consumables will be needed? • What will be the technical lifetime? • How much maintenance and repairs will be needed? • What and how much auxiliary materials and energy will be required? • What will be the aesthetic lifetime of the product?
Recovery	• How can the product be reused? • Will the components or materials be reused? • Can the product be quickly disassembled using common tools? • What materials will be recyclable? • Will recyclable materials be identifiable? • How will the product be disposed?

EXHIBIT 12-7 Typical questions for consideration of the environmental impacts of each life cycle stage. Adapted from Brezet and van Hemel (1997).

Step 3: Select DFE Guidelines

Guidelines help product design teams to make early DFE decisions without the type of detailed environmental impact analysis that is only possible after the design is more fully specified. Relevant guidelines may be selected based in part on the qualitative assessment of life cycle impacts (from step 2). Selecting relevant guidelines during the concept development phase allows the product development team to apply them throughout the product development project.

Exhibit 12-8 shows a compilation of DFE guidelines based on a study by Telenko et al. (2008). Each life cycle stage has its own DFE guidelines that provide product development teams with instructions on how to reduce the environmental impacts of a product. A more detailed list of DFE guidelines is provided in the appendix to this chapter. Many of the guidelines relate to selection of materials. This underscores the central role of materials in DFE.

Life Cycle Stage	Design for Environment Guidelines	
Materials	Sustainability of resources	• Specify renewable and abundant resources.* • Specify recyclable and/or recycled materials.* • Specify renewable forms of energy.*
	Healthy inputs and outputs	• Specify nonhazardous materials.* • Install protection against release of pollutants and hazardous substances. • Include labels and instructions for safe handling of toxic materials.*
Production	Minimal use of resources in production	• Employ as few manufacturing steps as possible.* • Specify materials that do not require surface treatments or coatings.* • Minimize the number of components.* • Specify lightweight materials and components.*
Distribution	Minimal use of resources in distribution	• Minimize packaging. • Use recyclable and/or reusable packaging materials. • Employ folding, nesting, or disassembly to distribute products in a compact state. • Apply structural techniques and materials to minimize the total volume of material.
Use	Efficiency of resources during use	• Implement default power-down for subsystems that are not in use. • Use feedback mechanisms to indicate how much energy or water are being consumed. • Implement intuitive controls for resource-saving features.
	Appropriate durability	• Consider aesthetics and functionality to ensure the aesthetic life is equal to the technical life. • Facilitate repair and upgrading. • Ensure minimal maintenance. • Minimize failure modes.
Recovery	Disassembly, separation, and purification	• Ensure that joints and fasteners are easily accessible.* • Specify joints and fasteners so that they are separable by hand or with common tools.* • Ensure that incompatible materials are easily separated.*

EXHIBIT 12-8 Design for environment guidelines arranged according to the life cycle stage of a product. Based on Telenko et al. (2008). Guidelines used in the Setu project are identified with an asterisk.

For the Setu project, the DFE experts provided the product development team with several guidelines. These guidelines are identified with an asterisk in Exhibit 12-8.

Step 4: Apply the DFE Guidelines to the Initial Product Design

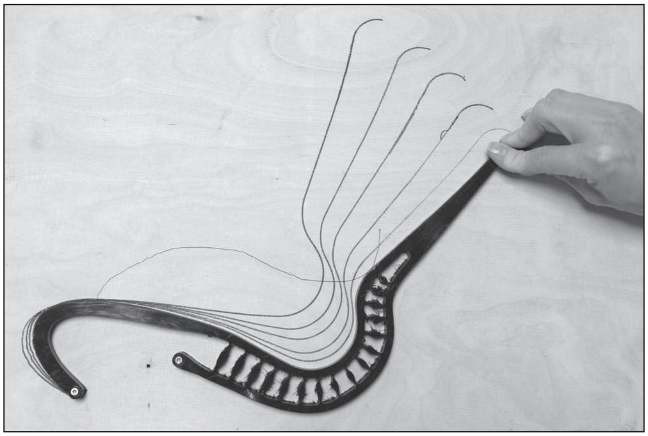
As the product architecture is developed during the system-level design phase (see Chapter 10, Product Architecture), some initial material choices are made along with some of the module design decisions. It is beneficial, therefore, to apply the relevant DFE guidelines (selected in step 3) at this point. In this way, the initial product design may have lower environmental impacts.

The Setu team wanted the chair to be lightweight in order to reduce materials use and transportation impacts (application of the DFE guideline: Specify lightweight materials and components). They achieved this by developing a concept and product architecture that avoided an under-seat tilt mechanism and other complexities. This helped to reduce the chair's weight by as much as 20 pounds (9 kg). The Setu team also looked for new ways to ease the disassembly of the Setu in order to facilitate recycling. They placed each joint where it is easily accessible and also ensured that Setu's components are separable by hand or with common tools (application of the DFE guidelines: Ensure that joints and fasteners are easily accessible; Specify joints and fasteners so that they are separable by hand or with common tools).

In the detail-design phase, the exact materials specifications, detailed geometry, and manufacturing processes are determined. Application of the DFE guidelines in detail design is essentially the same as in system-level design; however, at this point many more decisions are being made and environmental factors can be considered with greater precision. By specifying low-impact materials and reducing energy consumption, product development teams create more environmentally friendly products. Furthermore, the DFE guidelines may inspire product development teams to come up with improvement in the functionality and durability of the product, which may lead to significant lower environmental impacts.

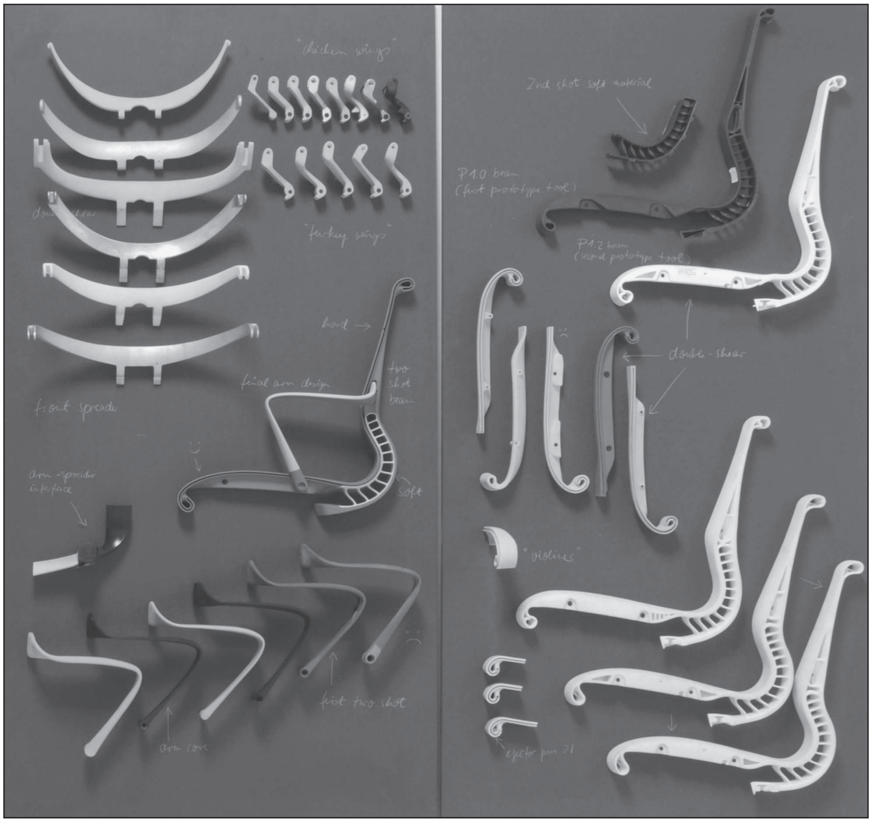
The Setu spine geometry, shown in Exhibit 12-9, was inspired by the human backbone. Studio 7.5 designers prototyped many iterations of the spine in order to achieve proper support and recline (see Exhibit 12-10). Once the shape of the spine was set, the team had to find materials that suited both the functional and environmental requirements.

EXHIBIT 12-9 The Setu spine was inspired by the human backbone.



Courtesy of Studio 7.5 and Herman Miller, Inc.

EXHIBIT 12-10 The design team prototyped many variations of Setu's spine and related components.



Courtesy of Studio 7.5 and Herman Miller, Inc.

To specify materials that fit the environmental and functional requirements, the development team used Herman Miller's proprietary materials database. The database, maintained together with MBDC, considers the safety and environmental impacts of each material and classifies them into one of four categories: green (little to no hazard), yellow (low to moderate hazard), orange (incomplete data), and red (high hazard). Herman Miller's aim was to use only materials that rank yellow or green for all new products.

For example, polyvinyl chloride (PVC) is classified as a red material. PVC is a polymer that is commonly used in furniture and other products due to its low cost and high strength. However, both the production and the incineration of PVC releases toxic emissions. To avoid using materials that are toxic to humans and the environment (application of the DFE guideline: Specify nonhazardous materials), the engineers specified safer materials such as polypropylene and avoided PVC entirely.

Step 5: Assess the Environmental Impacts

The next step is to assess, to the extent possible, the environmental impacts of the product over its entire life cycle. To do so with precision requires a detailed understanding of how the product is to be produced, distributed, used over its lifetime, and recycled or disposed at the end of its useful life. This assessment is generally done on the basis of the detailed bill of materials (BOM), including sources of energy, component material specifications, suppliers, transportation modes, waste streams, recycling methods, and disposal means. Several quantitative life cycle assessment (LCA) tools are available to conduct such an environmental assessment. These tools range in price and complexity and would be selected based on the types of materials and processes involved, and the precision required of the analysis.

LCA requires a significant amount of time, training, and data. Many LCA analyses are comparative and provide a basis for considering the environmental performance of product design alternatives. Commercial LCA software is becoming widely used in product design, and supporting data are available for common materials, production processes, transport methods, energy generation processes, and disposal scenarios.

Herman Miller uses their own proprietary DFE assessment tool, developed for them by MBDC. The DFE tool consists of a spreadsheet interface and the materials database using the color coding described above. The tool considers four factors for each component in the product:

1. ***Material chemistry:*** Fraction of the materials by weight that are the safest possible in terms of human toxicity and environmental concerns.
2. ***Recycled content:*** Fraction of the materials by weight that are postindustrial or postconsumer recycled content.
3. ***Disassembly:*** Fraction of the materials by weight that can be readily disassembled.
4. ***Recyclability:*** Fraction of the materials by weight that are recyclable.

Once the initial Setu design was established, the chair was divided into modules, with different teams assigned to develop each module. As each team designed their module, the DFE team assessed the design using the DFE tool.

Compare the Environmental Impacts to DFE Goals

This step compares the environmental impacts of the evolving design to the DFE goals established in the planning phase. If several design options were created in the detail-design phase, they may now be compared to judge which one has the lowest environmental impacts. Unless the product development team is very experienced in DFE, the design will generally have much room for improvement. Usually several DFE iterations are required before the team is satisfied that the product is as good as it should be from a DFE perspective.

Step 6: Refine the Product Design to Reduce or Eliminate the Environmental Impacts

The objective of this step and subsequent DFE iterations is to reduce or eliminate any significant environmental impacts through redesign. The process repeats until the environmental impacts have been reduced to an acceptable level and the environmental performance fits the DFE goals. Redesign for ongoing improvement of DFE may also continue after production begins. For the Aeron and Mirra chairs (shown in Exhibit 12-1), Herman

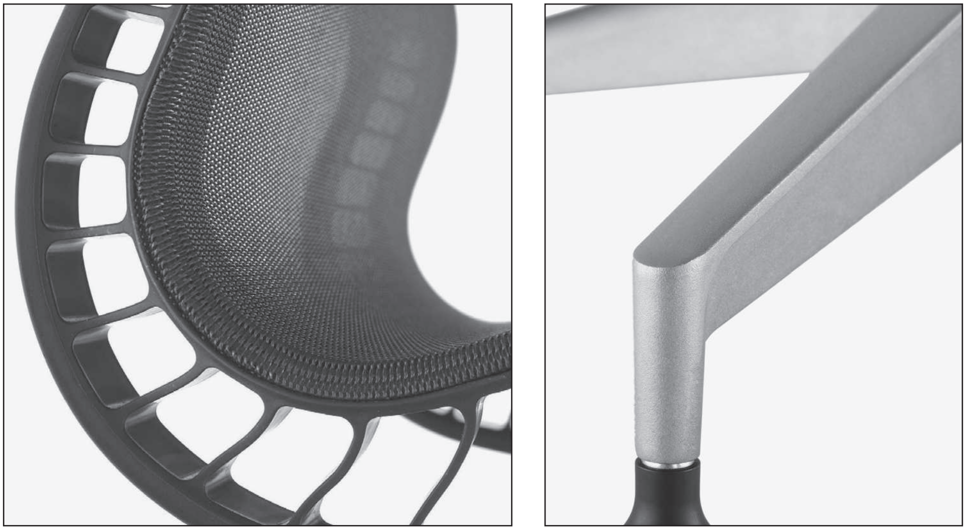


EXHIBIT 12-11 The final design of the Setu spine (left) and aluminum base (right).

Courtesy of Herman Miller, Inc.

Miller made several modifications to materials specifications and sources since the initial release of these products, reducing their environmental impacts.

After several design iterations, the Setu team developed a way to co-mold the spine using two different polypropylene materials that are compatible for recycling without separation. The inner and outer rails of the spine are made of a polypropylene-and-glass composite, while the connecting spokes are molded using a more flexible polypropylene-and-rubber composite (see Exhibit 12-11). Setu's aluminum base is an example of "minimal design." Uncoated and unpolished, with no finishing labor and no harmful toxins, it is durable and has less environmental impacts than traditionally finished chair bases.

One of the difficult trade-offs addressed in the development of Setu was related to selection of materials for the arms of the chair. While they were determined to avoid using PVC, the team was not able to mold the arms using all olefinic materials (such as polypropylene) due to concerns of durability and fatigue failure. The Setu arms, therefore, were molded from nylon and over-molded with a thermoplastic elastomer. Because these materials are not chemically compatible for recycling, this decision limited the chair's overall recyclability.

Step 7: Reflect on the DFE Process and Results

As with every aspect of the product development process, the final activity is to ask:

- How well did we execute the DFE process?
- How can our DFE process be improved?
- What DFE improvements can be made on derivative and future products?

DFE Assessment Factor	Setu Score	Factor Weight	Weighted Score
Material Chemistry	50%	33.3%	16.7%
Recycled Content	44%	8.4%	3.7%
Disassembly	86%	33.3%	28.6%
Recyclability	92%	25.0%	23.0%
Overall Score		**100%**	**72%**

EXHIBIT 12-12 Herman Miller's DFE assessment tool considers four factors and computes the weighted overall score of 72 percent for the Setu chair.

Based on Herman Miller's DFE assessment tool, on a scale of 0 to 100 percent, with 100 percent being a truly "cradle-to-cradle" product, the Setu chair achieved a rating of 72 percent, as shown in Exhibit 12-12.

The Setu team was pleased with the chair in terms of ease of disassembly and feasibility of recycling. Over the course of developing the Setu, the chair's recyclability score moved up and down and eventually dropped from 99 percent to 92 percent due to the material selection trade-off in design of the arms. One very important achievement made during the development of the Setu to enable its recyclability was a change in the spine's materials. Early iterations used dissimilar materials bonded together, which could not be recycled. The DFE team challenged the Setu team to innovate further. The resulting solution is constructed of two materials that are compatible for recycling without separation. Unfortunately, such a solution could not be developed for the Setu arms, and incompatible bonded materials were used there.

While highly successful in terms of implementing DFE, the Setu chair still had some negative environmental impacts, particularly in terms of material chemistry and use of recycled content, as shown in Exhibit 12-12. This reflects the reality that creating a perfect product from a DFE perspective is a goal that may take years to achieve. Effective DFE requires a product development team that strives for continuous improvement. The DFE team may be able to further develop the Setu chair to reduce some of the known impacts. For example, molding the Setu arms entirely using polypropylene would likely improve recyclability and reduce cost, but would also require addressing several very challenging technical issues.

To further improve their DFE process, Herman Miller began to use LCA software to monitor their DFE results and to guide further refinement of their products. They next planned to integrate "carbon footprint" into their DFE tool. The carbon footprint of a product is the amount of greenhouse gas emissions caused by the product, usually expressed in terms of the equivalent mass of CO_2 emitted. The consideration of carbon footprint would further affect Herman Miller's material choices. For example, based only on recyclability and environmental toxicity, aluminum is an environmentally friendly material. However, considering the carbon footprint of aluminum, it may be a less favorable choice (compared to steel, for example) due to the amount of energy required to produce new aluminum. Recycled aluminum, however, uses much less energy, so this analysis also depends upon the sources of the materials and energy used to process the metals.

Summary

Every product has environmental impacts over its life cycle. Design for environment (DFE) provides companies with a practical method to minimize or eliminate these environmental impacts.

- Effective DFE maintains or improves product quality and cost while reducing environmental impacts.
- DFE expands the traditional manufacturer's focus to consider the full product life cycle and its relationship to the environment. It begins with the extraction and processing of raw materials from natural resources, followed by production, distribution, and use of the product. Finally, at the end of the product's useful life are several recovery options: remanufacturing or reuse of components, recycling of materials, or disposal through incineration or deposition in a landfill, to reintegrate the product into a closed-loop cycle.
- DFE may involve activities throughout the product development process and requires an interdisciplinary approach. Industrial design, engineering, purchasing, and marketing all work together in the development of environmentally friendly products.
- The DFE process consists of seven steps. Product development teams will likely repeat some steps several times.
    1. Set the DFE agenda: drivers, goals, and team.
    2. Identify potential environmental impacts.
    3. Select DFE guidelines.
    4. Apply the DFE guidelines to the initial product design.
    5. Assess the environmental impacts.
    6. Refine the product design to reduce or eliminate the environmental impacts.
    7. Reflect on the DFE process and results.

References and Bibliography

Many current resources are available on the Internet via
www.ulrich-eppinger.net

There are several texts covering the topic of DFE. Bhamra and Lofthouse provide an introduction to design for sustainability and a description of several strategic tools that can be used for DFE such as the EcoDesign Web. Fiksel's book is a comprehensive guide to DFE as a life cycle approach to new product and process development. Lewis et al. provide an overview and description of the environmental impacts and several environmental assessment tools.

Bhamra, T., and V. Lofthouse, *Design for Sustainability: A Practical Approach,* Gower, UK, 2007.

Fiksel, J. R., *Design for Environment: A Guide to Sustainable Product Development,* second edition, McGraw-Hill, New York, 2009.

Lewis, H., J. Gertsakis, and T. Grant, *Design and Environment: A Global Guide to Designing Greener Goods,* Greenleaf Publishing Limited, Sheffield, UK, 2001.

A number of authors have argued persuasively for due consideration of environmental impacts in design. Burall concluded that there is no longer a conflict between a green approach to design and business success. McDonough and Braungart explain that the conflict between industry and the environment is not an indictment of commerce but rather an outgrowth of purely opportunistic design. Papanek challenged designers to face their social and environmental responsibilities instead of only commercial interests. *The Brundtland Report* (1987) first defined the term *sustainable development.*

Burall, P., *Green Design,* Design Council, London, 1991.

McDonough, W., and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things,* North Point Press, New York, 2002.

Papanek, V., *Design for the Real World: Human Ecology and Social Change,* Van Nostrand Reinhold Co., New York, 1971.

World Commission on Environment and Development, *The Brundtland Report: Our Common Future,* Oxford University Press, London, 1987.

Portions of the DFE method presented in this chapter are derived from various sources. The internal and external drivers for DFE are based on Brezet and van Hemel's Ecodesign work. The DFE goals are adapted from the environmental strategies listed by Giudice et al. The DFE guidelines are derived from the comprehensive compilation by Telenko et al. The materials-based emphasis of DFE reflects the cradle-to-cradle concept explained by McDonough and Braungart.

Brezet, H., and C. van Hemel, *Ecodesign: A Promising Approach to Sustainable Production and Consumption*, TU Delft, Netherlands, 1997.

Giudice, F., G. La Rosa, and A. Risitano, *Product Design for the Environment: A Life Cycle Approach*, CRC Press Taylor & Francis Group, Boca Raton, FL, 2006.

Telenko, C., C. C. Seepersad, and M. E. Webber, *A Compilation of Design for Environment Principles and Guidelines*, ASME DETC Design for Manufacturing and the Life Cycle Conference, New York, 2008.

The International Organization for Standardization (ISO) has developed internationally agreed standards for LCA, known as ISO 14040.

International Organization for Standardization, *Environmental Management: Life Cycle Assessment—Principles and Framework*, European Committee for Standardization, Brussels, 2006.

Exercises

1. List at least 10 types of environmental impacts over the life cycle of your personal computer or mobile phone. Chart these as in Exhibit 12-6, representing your judgment of the relative impact of each life cycle stage.
2. Disassemble a simple product, such as a ballpoint pen. Suggest two ways to reduce its environmental impacts.
3. For the product considered in Exercise 1, compute its environmental impact score using any LCA analysis tool available to you.

Thought Questions

1. What are some of the ways in which you have become more aware of your own environmental impact in recent years?
2. For the Setu chair, what types of environmental impacts would be in the use stage of its life cycle?
3. In what ways can DFE help to improve the quality of a product, in terms of its functionality, reliability, durability, and reparability?
4. For each life cycle stage, identify a product or service that has high environmental impacts during the particular life cycle stage. Then, suggest a new or existing product or service that provides the same functionality with lower (or without any) environmental impacts.
5. How would you explicitly include renewable and nonrenewable energy in the life cycle diagram in Exhibit 12-3? Draw such a diagram and explain it.
6. Explain the relationship between DFE and DFM. Consider, for example, those DFE guidelines related to production in Exhibit 12-8.
7. Consider the DFE assessment tool used by Herman Miller (Exhibit 12-12), which computed the weighted sum of scores for material chemistry, use of recycled content, ease of disassembly, and recyclability. What modifications would you propose to create a DFE assessment tool for a different type of product, such as an automobile or a mobile phone?

Appendix

Design for Environment Guidelines

Telenko et al. (2008) compiled an extensive list of DFE guidelines based on a number of sources covering a range of industries. Each life cycle stage has its own DFE guidelines that provide product development teams with suggestions to reduce environmental impacts. The list below is based upon the compilation by Telenko et al.

Life Cycle Stage: Materials

Ensure Sustainability of Resources

1. Specify renewable and abundant resources.
2. Specify recyclable or recycled materials, especially those within the company or for which a market exists or needs to be stimulated.
3. Layer recycled and virgin material where virgin material is necessary.
4. Exploit unique properties of recycled materials.
5. Employ common and remanufactured components across models.
6. Specify mutually compatible materials and fasteners for recycling.
7. Specify one type of material for the product and its subassemblies.
8. Specify noncomposite, nonblended materials and no alloys.
9. Specify renewable forms of energy.

Ensure Healthy Inputs and Outputs

10. Install protection against release of pollutants and hazardous substances.
11. Specify nonhazardous and otherwise environmentally "clean" substances, especially in regards to user health.
12. Ensure that wastes are water-based or biodegradable.
13. Specify the cleanest source of energy.
14. Include labels and instructions for safe handling of toxic materials.
15. Specify clean production processes for the product and in selection of components.
16. Concentrate toxic elements for easy removal and treatment.

Life Cycle Stage: Production

Ensure Minimal Use of Resources in Production

17. Apply structural techniques and materials to minimize the total volume of material.
18. Specify materials that do not require additional surface treatment, coatings, or inks.
19. Structure the product to avoid rejects and minimize material waste in production.
20. Minimize the number of components.
21. Specify materials with low-intensity production and agriculture.
22. Specify clean, high-efficiency production processes.
23. Employ as few manufacturing steps as possible.

Life Cycle Phase: Distribution

Ensure Minimal Use of Resources in Distribution

24. Replace the functions and appeals of packaging through the product's design.
25. Employ folding, nesting, or disassembly to distribute products in a compact state.
26. Specify lightweight materials and components.

Life Cycle Stage: Use

Ensure Efficiency of Resources During Product Use

27. Implement reusable supplies for ensuring the maximum usefulness of consumables.
28. Implement fail-safes against heat and material loss.
29. Minimize the volume and weight of parts and materials to which energy is transferred.
30. Specify best-in-class, energy-efficient components.
31. Implement default power-down for subsystems that are not in use.
32. Ensure rapid warm-up and power-down.
33. Maximize system efficiency for an entire range of usage conditions.
34. Interconnect available flows of energy and materials within the product and between the product and its environment.
35. Incorporate partial operation and permit users to turn off systems partially or completely.
36. Use feedback mechanisms to indicate how much energy or water is being consumed.
37. Incorporate intuitive controls for resource-saving features.
38. Incorporate features that prevent waste of materials by the user.
39. Use default mechanisms to automatically reset the product to its most efficient setting.

Ensure Appropriate Durability of the Product and Components

40. Reutilize high-embedded energy components.
41. Plan for ongoing efficiency improvements.
42. Improve aesthetics and functionality to ensure the aesthetic life is equal to the technical life.
43. Ensure minimal maintenance and minimize failure modes in the product and its components.
44. Specify better materials, surface treatments, or structural arrangements to protect products from dirt, corrosion, and wear.
45. Indicate on the product which parts are to be cleaned/maintained in a specific way.
46. Make wear detectable.
47. Allow easy repair and upgrading, especially for components that experience rapid change.
48. Require few service and inspection tools.
49. Facilitate testing of components.
50. Allow for repetitive disassembly and reassembly.

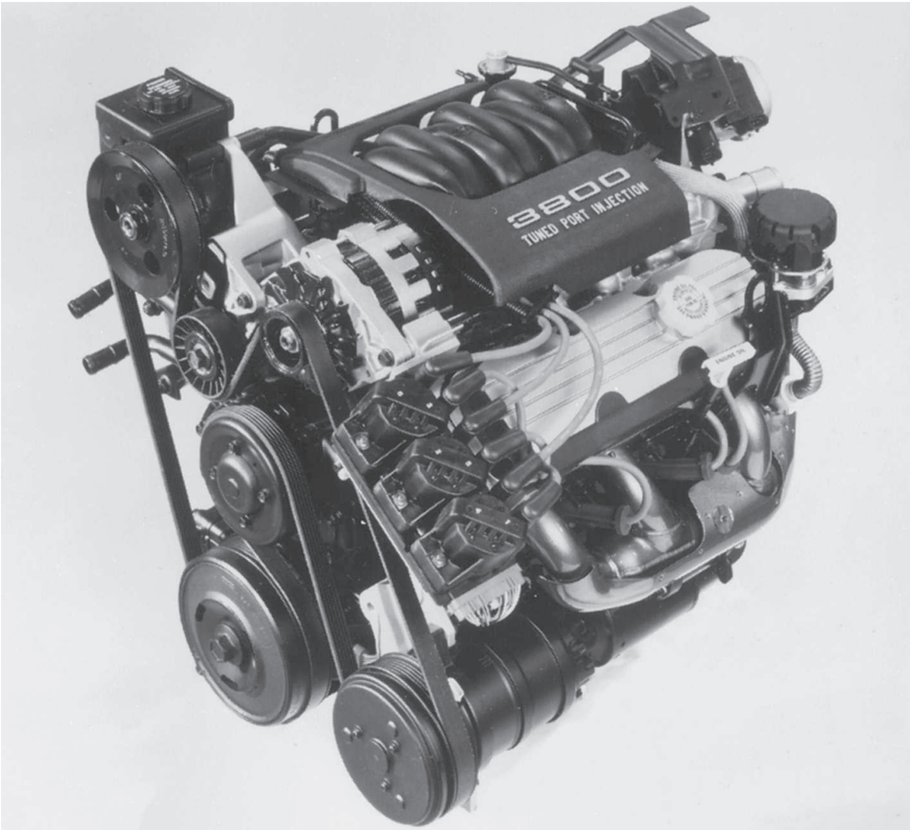
Life Cycle Stage: Recovery

Enable Disassembly, Separation, and Purification of Materials and Components

51. Indicate on the product how it should be opened and make access points obvious.
52. Ensure that joints and fasteners are easily accessible.
53. Maintain stability and part placement during disassembly.
54. Minimize the number and variety of joining elements.
55. Ensure that destructive disassembly techniques do not harm people or reusable components.
56. Ensure that reusable parts can be cleaned easily and without damage.
57. Ensure that incompatible materials are easily separated.
58. Make component interfaces simple and reversibly separable.
59. Organize a product or system into hierarchical modules by aesthetic, repair, and end-of-life protocol.
60. Implement reusable/swappable platforms, modules, and components.
61. Condense into a minimal number of parts.
62. Specify compatible adhesives, labels, surface coatings, pigments, and the like that do not interfere with cleaning.
63. Employ one disassembly direction without reorientation.
64. Specify all joints so that they are separable by hand or only a few, simple tools.
65. Minimize the number and length of operations for detachment.
66. Mark materials in molds with types and reutilization protocols.
67. Use a shallow or open structure for easy access to subassemblies.

CHAPTER THIRTEEN

Design for Manufacturing

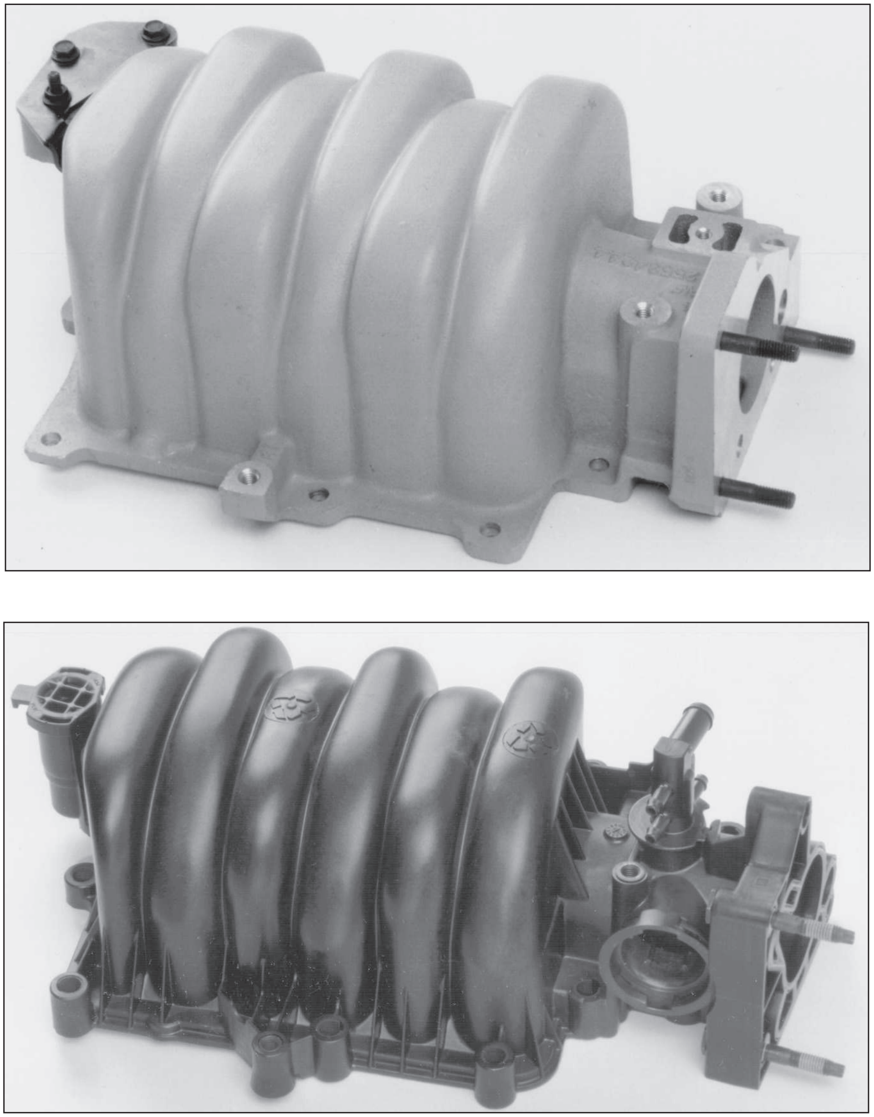


Courtesy of General Motors Corp.

EXHIBIT 13-1
The General Motors 3.8-liter V6 engine.

General Motors Powertrain Division manufactures about 3,500 3.8-liter V6 engines every day (Exhibit 13-1). Facing such high production volumes, the company had a strong interest in reducing the cost of the engine while simultaneously enhancing its quality. A team was formed to improve one of the most expensive subassemblies in the engine: the air intake manifold. (The intake manifold's primary function is to route air from the throttle to the intake valves at the cylinders.) The original and redesigned intake manifold assemblies are shown in Exhibit 13-2. This chapter presents a method of design for manufacturing using the GM V6 intake manifold as an example.

EXHIBIT 13-2
The original and redesigned air intake manifolds. The body of the original manifold (top) is made of cast aluminum. The redesigned manifold (bottom) is made of molded thermoplastic composite.



Photos by Stuart Cohen

Design for Manufacturing Defined

Customer needs and product specifications are useful for guiding the concept phase of product development; however, during the later development activities teams often have difficulty linking needs and specifications to the specific design issues they face. For this reason, many teams practice "design for X" (DFX) methodologies, where X may correspond to one of dozens of quality criteria such as reliability, robustness, serviceability, environmental impact, or manufacturability. The most common of these methodologies is *design for manufacturing* (DFM), which is of universal importance because it directly addresses manufacturing costs.

This chapter is primarily about DFM, but it is also intended to illustrate, by example, these general principles, which apply to methodologies for achieving any of the Xs in DFX:

- Detail-design decisions can have substantial impact on product quality and cost.
- Development teams face multiple, and often conflicting, goals.
- It is important to have metrics with which to compare alternative designs.
- Dramatic improvements often require substantial creative efforts early in the process.
- A well-defined method assists the decision-making process.

Manufacturing cost is a key determinant of the economic success of a product. In simple terms, economic success depends on the profit margin earned on each sale of the product and on how many units of the product the firm can sell. Profit margin is the difference between the manufacturer's selling price and the cost of making the product. The number of units sold and the sales price are to a large degree determined by the overall quality of the product. Economically successful design is therefore about ensuring high product quality while minimizing manufacturing cost. DFM is one method for achieving this goal; effective DFM practice leads to low manufacturing costs without sacrificing product quality. (See Chapter 17, Product Development Economics, for a more detailed discussion of models relating manufacturing costs to economic success.)

DFM Requires a Cross-Functional Team

Design for manufacturing is one of the most integrative practices involved in product development. DFM utilizes information of several types, including (1) sketches, drawings, product specifications, and design alternatives; (2) a detailed understanding of production and assembly processes; and (3) estimates of manufacturing costs, production volumes, and ramp-up timing. DFM therefore requires the contributions of most members of the development team as well as outside experts. DFM efforts commonly draw upon expertise from manufacturing engineers, cost accountants, and production personnel, in addition to product designers. Many companies use structured, team-based workshops to facilitate the integration and sharing of views required for DFM.

DFM Is Performed throughout the Development Process

DFM begins during the concept development phase, when the product's functions and specifications are being determined. When choosing a product concept, cost is almost always one of the criteria on which the decision is made—even though cost estimates at this phase are highly subjective and approximate. When product specifications are finalized, the team makes trade-offs between desired performance characteristics. For example, weight reduction may increase manufacturing costs. At this point, the team may have an approximate bill of materials (a list of parts) with estimates of costs. During the system-level design phase of development, the team makes decisions about how to break up the product into individual components, based in large measure on the expected cost and manufacturing complexity implications. Accurate cost estimates finally become available during the detail-design phase of development, when many more decisions are driven by manufacturing concerns.

Overview of the DFM Process

Our DFM method is illustrated in Exhibit 13-3. It consists of five steps plus iteration:

1. Estimate the manufacturing costs.
2. Reduce the costs of components.
3. Reduce the costs of assembly.
4. Reduce the costs of supporting production.
5. Consider the impact of DFM decisions on other factors.

As shown in Exhibit 13-3, the DFM method begins with the estimation of the manufacturing cost of the proposed design. This helps the team to determine at a general level which aspects of the design—components, assembly, or support—are most costly. The team then directs its attention to the appropriate areas in the subsequent steps. This process is iterative. It is not unusual to recompute the manufacturing cost estimate and to improve the design of the product dozens of times before agreeing that it is good enough. As long as the product design is improving, these DFM iterations may continue even until pilot production begins. At some point, the design is frozen (or "released"), and any further modifications are considered formal "engineering changes" or become part of the next generation of the product.

In the next section, we use the original GM V6 intake manifold as an example and explain how manufacturing costs are determined. Then, recognizing that accurate cost estimates are difficult (if not impossible) to obtain, we present several useful methods for reducing the costs of components, assembly, and production support. We use the redesigned intake manifold and other products as examples to illustrate these DFM principles. Finally, we discuss the results achieved through DFM and some of the broader implications of DFM decisions.

Step 1: Estimate the Manufacturing Costs

Exhibit 13-4 shows a simple input-output model of a manufacturing system. The inputs include raw materials, purchased components, employees' efforts, energy, and equipment. The outputs include finished goods and waste. Manufacturing cost is the sum of all of the expenditures for the inputs of the system and for disposal of the wastes produced by the system. As the metric of cost for a product, firms generally use *unit manufacturing cost,* which is computed by dividing the total manufacturing costs for some period (usually a quarter or a year) by the number of units of the product manufactured during that period. This simple concept is complicated in practice by several issues:

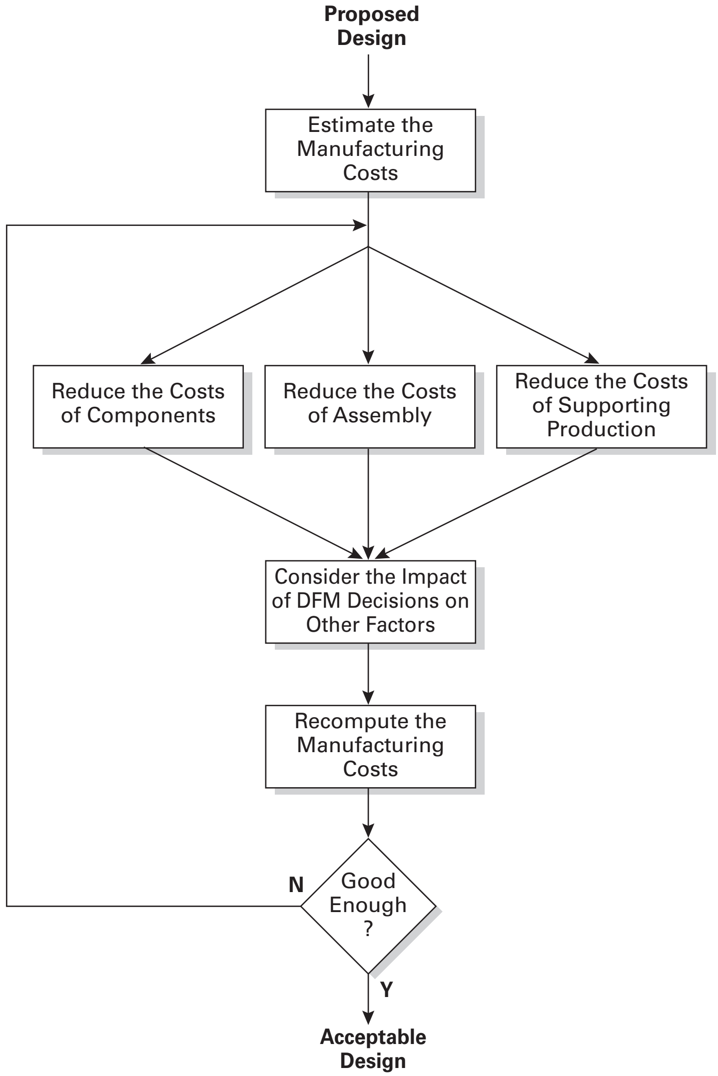


EXHIBIT 13-3
The design for manufacturing (DFM) method.

- What are the boundaries of the manufacturing system? Should the field service operations be included? What about product development activities?
- How do we "charge" the product for the use of expensive general-purpose equipment that lasts for many years?
- How are costs allocated among more than one product line in large, multiproduct manufacturing systems?

These are issues around which much of the field of managerial accounting is built, and we do not treat them in depth here. Nevertheless, we will be mindful of these complications as we discuss cost and DFM in this chapter.

EXHIBIT 13-4 A simple input-output model of a manufacturing system.

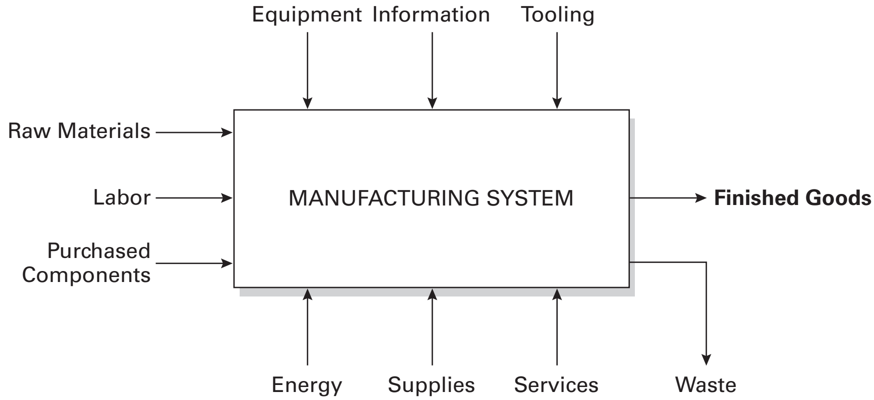


Exhibit 13-5 shows one way of categorizing the elements of manufacturing cost. Under this scheme, the unit manufacturing cost of a product consists of costs in three categories:

1. ***Component costs:*** The *components* of a product (also simply called parts of the product) may include *standard parts* purchased from suppliers. Examples of standard components include motors, switches, electronic chips, and screws. Other components are *custom parts,* made according to the manufacturer's design from raw materials, such as sheet steel, plastic pellets, or aluminum bars. Some custom components are made in the manufacturer's own plant, while others may be produced by suppliers according to the manufacturer's design specifications.

2. ***Assembly costs:*** Discrete goods are generally assembled from parts. The process of assembling almost always incurs labor costs and may also incur costs for equipment and tooling.

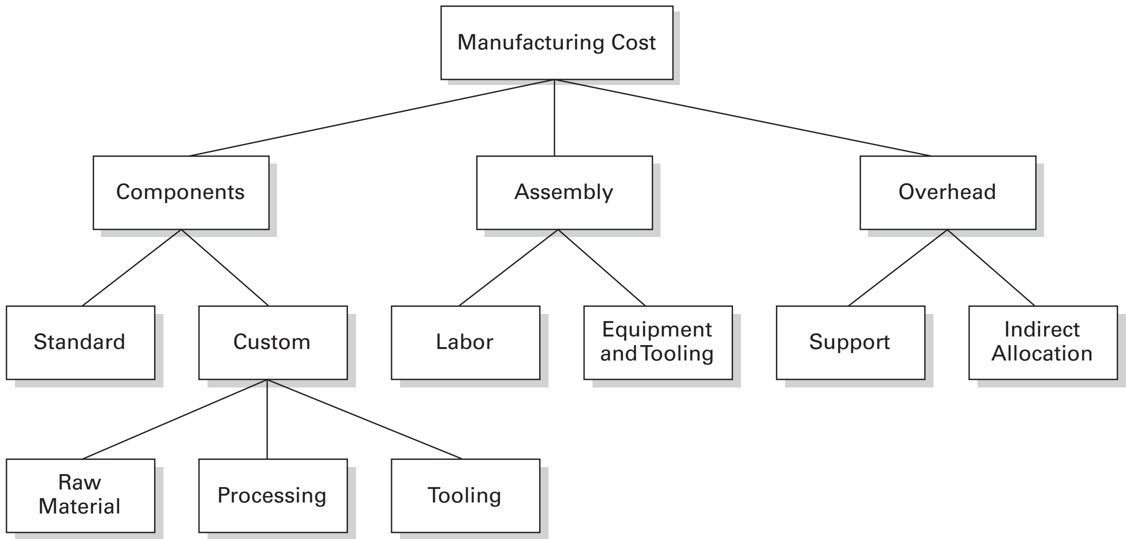


EXHIBIT 13-5 Elements of the manufacturing cost of a product.

3. *Overhead costs:* Overhead is the category used to encompass all of the other costs. We find it useful to distinguish between two types of overhead: *support costs* and other *indirect allocations*. Support costs are the costs associated with materials handling, quality assurance, purchasing, shipping, receiving, facilities, and equipment/tooling maintenance (among others). These are the support systems required to manufacture the product, and these costs do greatly depend upon the product design. Nevertheless, because these costs are often shared by more than one product line, they are lumped together in the category of overhead. Indirect allocations are the costs of manufacturing that cannot be directly linked to a particular product but that must be paid for to be in business. For example, the salary of the security guard and the cost of maintenance to the building and grounds are indirect costs because these activities are shared among several different products and are difficult to allocate directly to a specific product. Because indirect costs are not specifically linked to the design of the product, they are not relevant to DFM, even though they do contribute to the cost of the product.

Transportation Costs

The model of manufacturing cost in Exhibit 13-5 does not include any costs for transporting finished goods through the distribution system. Manufacturing often occurs at a location a great distance from the eventual customer. Although the DFM method presented here does not explicitly include transportation expense, estimating those costs is relatively easy. For instance, most goods are transported overseas using standard shipping containers, which hold about 70 cubic meters of cargo. In most cases, these containers are shipped from one location to another at a fixed cost. Currently the cost of shipping a container between Asia and the United States is roughly 6,000 USD, resulting in a shipping cost rate of 86 USD/m^3. Rates for air freight and trucking, although based on a combination of weight and volume, are also readily available. Based on these rates, the product design team can easily include transportation costs in its analysis, and doing so may be warranted when the team faces design decisions involving the physical volume or weight of the product.

Fixed Costs versus Variable Costs

Another way to divide manufacturing costs is between *fixed costs* and *variable costs*. Fixed costs are those that are incurred in a predetermined amount, regardless of how many units of the product are manufactured. Purchasing the injection mold required for the new intake manifold is an example of a fixed cost. Whether 1,000 or 1 million units are produced, the fixed cost of the mold is incurred and does not change. Another example is the cost of setting up the factory work area for the intake manifold assembly line. This cost is also fixed, regardless of how many units are produced. Despite the terminology, however, no cost is truly fixed. If we quadruple the production quantity, we may have to build another production line. Conversely, we may be able to consolidate two assembly cells if we cannot use all the capacity due to dramatically lower production quantities. When considering a cost as fixed, ranges of production quantities and the assumed time horizon should be specified.

Variable costs are those incurred in direct proportion to the number of units produced. For example, the cost of raw materials is directly proportional to how many intake manifolds are produced, and therefore to how many 3.8-liter V6 engines are made. Assembly labor is sometimes considered a variable cost as well because many firms can adjust the staffing of assembly operations by shifting workers to other areas on short notice.

The Bill of Materials

Because manufacturing cost estimation is fundamental to DFM, it is useful to keep this information well organized. Exhibit 13-6 shows an information system for recording manufacturing cost estimates. It basically consists of a bill of materials (BOM) augmented with cost information. The BOM (usually pronounced bomb) is a list of each individual component in the product. Frequently the BOM is created using an indented format in which the assembly "tree structure" is illustrated by the indentation of components and subassembly names.

The columns of the BOM show the cost estimates broken down into fixed and variable costs. The variable costs may include materials, machine time, and labor. Fixed costs consist of tooling and other nonrecurring expenses (NRE) such as specialized equipment and one-time setup costs. The tooling lifetime is used to compute the unit fixed cost (unless the tool's expected lifetime exceeds the product's lifetime volume, in which case the lower product volume is used). To compute total cost, overhead is added according to the firm's accepted cost accounting scheme. Note that additional fixed costs, such as depreciation of capital equipment used for several products, are often also included in the overhead charge.

Component	Purchased Materials	Processing (Machine + Labor)	Assembly (Labor)	Total Unit Variable Cost	Tooling and Other NRE, K$	Tooling Lifetime, K units	Total Unit Fixed Cost	Total Cost
Manifold machined casting	12.83	5.23		18.06	1960	500+	0.50	18.56
EGR return pipe	1.30		0.15	1.45				1.45
PCV assembly								
Valve	1.35		0.14	1.49				1.49
Gasket	0.05		0.13	0.18				0.18
Cover	0.76		0.13	0.89				0.89
Screws (3)	0.06		0.15	0.21				0.21
Vacuum source block assembly								
Block	0.95		0.13	1.08				1.08
Gasket	0.03		0.05	0.08				0.08
Screw	0.02		0.09	0.11				0.11
Total Direct Costs	17.35	5.23	0.95	23.53	1960		0.50	24.03
Overhead Charges	2.60	9.42	1.71				0.75	14.48
Total Cost								**38.51**

EXHIBIT 13-6 Indented bill of materials showing cost estimates for the original intake manifold and related components. The EGR (exhaust gas recirculation), PCV (positive crankcase ventilation), and vacuum block components are included here to facilitate comparison with the redesigned manifold assembly.

Estimating the Costs of Standard Components

The costs of standard components are estimated by either (1) comparing each part to a substantially similar part the firm is already producing or purchasing in comparable volumes or (2) soliciting price quotes from vendors or suppliers. The costs of minor components (e.g., bolts, springs, and inserts) are usually obtained from the firm's experience with similar components, while the costs of major components are usually obtained from vendor quotes.

In obtaining price quotes, the estimated production quantities are extremely important. For example, the unit price on a purchase of a dozen screws or inserts may be 10 times higher than the unit prices paid by GM when purchasing 100,000 of these parts every month. If the anticipated production quantities are high enough, an application engineer or sales engineer is usually quite willing to work with the development team to specify a component properly. For internally fabricated standard components, if the required quantities are high, there may not be available production capacity, necessitating the purchase of additional equipment or the use of outside suppliers.

Some suppliers will design and fabricate a custom variation to a standard component if production quantities are high enough. For example, small electric motors, such as those found in powered hand tools, are often designed and built specifically for the product application. If the production quantities are high enough (say, 100,000 per year in this case), these custom motors are quite economical ($1 to $5 per unit, depending on the performance characteristics). For the intake manifold, the volumes are sufficiently high that custom studs, bushings, and other parts may not cost much more than standard components. However, as we discuss later, introducing new parts can add substantial cost and complexity to the production system and field service operations, which increases the support costs.

Vendors for most standard components can be found in the *Thomas Register of American Manufacturers* or by looking for company names on components used in related products. To obtain a price quote, first request a catalog or product literature (now generally available on the Internet). Then, either choose a part number or, if a custom component will be used, write a one-page description of the requirements of the component. Next, telephone the vendor, ask to speak to someone in "sales," and request price information. Make sure to inform vendors that the information is for estimation purposes only; otherwise, they may claim they do not have enough information to determine exact prices.

Estimating the Costs of Custom Components

Custom components, which are parts designed especially for the product, are made by the manufacturer or by a supplier. Most custom components are produced using the same types of production processes as standard components (e.g., injection molding, stamping, machining); however, custom parts are typically special-purpose parts, useful only in a particular manufacturer's products.

When the custom component is a single part, we estimate its cost by adding up the costs of raw materials, processing, and tooling. In cases where the custom component is actually an assembly of several parts, then we consider it a "product" in and of itself; to arrive at the cost of this "product" we estimate the cost of each subcomponent and then add assembly and overhead costs (these costs are described below). For the purposes of this explanation, we assume the component is a single part.

The raw materials costs can be estimated by computing the mass of the part, allowing for some scrap (e.g., 5 percent to 50 percent for an injection molded part, and 25 percent

EXHIBIT 13-7
Cost estimate for the original intake manifold. Note that the processing costs for casting and machining reflect the costs for a complete casting line and several machining stations.

Variable Cost		
Materials	5.7 kg aluminum at $2.25/kg	$12.83
Processing (casting)	150 units/hr at $530/hr	3.53
Processing (machining)	200 units/hr at $340/hr	1.70
Fixed Cost		
Tooling for casting	$160,000/tool at 500K units/tool (lifetime)	0.32
Machine tools and fixtures	$1,800,000/line at 10M units (lifetime)	0.18
Total Direct Cost		**$18.56**
Overhead charges		$12.09
Total Unit Cost		**$30.65**

to 100 percent for a sheet metal part), and multiplying by the cost (per unit mass) of the raw material. A table of raw material costs is given in Appendix A (Exhibit 13-17).

Processing costs include costs for the operator(s) of the processing machinery as well as the cost of using the equipment itself. Most standard processing equipment costs between $25 per hour (a simple stamping press) and $75 per hour (a medium-sized, computer-controlled milling machine) to operate, including depreciation, maintenance, utilities, and labor costs. Estimating the processing time generally requires experience with the type of equipment to be used. However, it is useful to understand the range of typical costs for common production processes. For this purpose, tables of approximate processing times and costs are given in Appendix B for a variety of stampings, castings, injection moldings, and machined parts.

Tooling costs are incurred for the design and fabrication of the cutters, molds, dies, or fixtures required to use certain machinery to fabricate parts. For example, an injection molding machine requires a custom injection mold for every different type of part it produces. These molds generally range in cost from $10,000 to $500,000. Approximate tooling costs are also given for the parts listed in Appendix B. The unit tooling cost is simply the cost of the tooling divided by the number of units to be made over the life of the tool. A high-quality injection mold or stamping die can usually be used for a few million parts.

The cost of the original intake manifold's machined casting is estimated as shown in Exhibit 13-7. Note that the estimate reveals that the cost is dominated by the expense of the aluminum material. We will see that the redesign using a composite material not only reduced the material costs but also eliminated machining and allowed many features to be formed into the molded body.

Estimating the Cost of Assembly

Products made of more than one part require assembly. For products made in quantities of less than several hundred thousand units per year, this assembly is almost always performed manually. One exception to this generalization is the assembly of electronic circuit boards, which is now almost always done automatically, even at relatively low volumes.

Manual assembly costs can be estimated by summing the estimated time of each assembly operation and multiplying by a labor rate. Assembly operations require from about 4 seconds to about 60 seconds each, depending upon the size of the parts, the

EXHIBIT 13-8
Assembly cost estimation for the PCV valve assembly of the redesigned intake manifold.

Component	Quantity	Handling Time	Insertion Time	Total Time
Valve	1	1.50	1.50	3.00
O-rings	2	2.25	4.00	12.50
Spring	1	2.25	6.00	8.25
Cover	1	1.95	6.00	7.95
Total Time (seconds)				**31.70**
Assembly Cost at $45/hour				**$0.40**

Source: Manual assembly tables in Boothroyd and Dewhurst, 1989

difficulty of the operation, and the production quantities. At high volumes, workers can specialize in a particular set of operations, and special fixtures and tools can assist the assembly. Appendix C contains a table of approximate times for manual assembly of various products, which is helpful in estimating the range of times required for assembly operations. A popular method for estimating assembly times has been developed over the past 30 years by Boothroyd Dewhurst Inc. and is now available as a software tool. This system involves a tabular information system for keeping track of the estimated assembly times for each part. The system is supported by a comprehensive database of standard handling and insertion times for a wide range of situations. Special software is also available for estimating the assembly cost of electronic circuit boards.

Assembly labor can cost from less than $1 per hour in low-wage countries to more than $40 per hour in some industrialized nations. In the United States, assembly labor is likely to cost between $10 and $20 per hour. (Each firm has different assembly labor cost structures, and some industries, such as the automobile and aircraft industries, have substantially higher cost structures.) These figures include an allowance for benefits and other worker-related expenses and are meant to reflect the true cost to the firm of assembly labor.

Consider the redesigned intake manifold. The assembly cost of the PCV (positive crankcase ventilation) valve assembly is estimated as shown in Exhibit 13-8.

Estimating the Overhead Costs

Accurately estimating overhead costs for a new product is difficult, and the industry practices are not very satisfying. Nevertheless, we will describe the standard industry practice here and identify some of its problems. Applying the overhead estimation schemes used by most firms is simple. Estimating the actual overhead costs incurred by the firm due to a particular product is not. The indirect costs of supporting production are very difficult to track and assign to particular product lines. The future costs of supporting production are even more difficult to predict for a new product.

Most firms assign overhead charges by using *overhead rates* (also called burden rates). Overhead rates are typically applied to one or two *cost drivers*. Cost drivers are parameters of the product that are directly measurable. Overhead charges are added to direct costs in proportion to the drivers. Common cost drivers are the cost of any purchased materials, the cost of assembly labor, and the number of hours of equipment time the product consumes. For example, the overhead rate for purchased materials might be 10 percent and the overhead rate for assembly labor might be 80 percent. (Of course, purchased components already have the vendor's overhead included in the price; we only add the purchasing overhead.) Under these conditions, a product containing $100 of purchased components and $10 of assembly labor would incur $18 of overhead costs

(10 percent of $100 plus 80 percent of $10). Some typical overhead structures are given in Appendix D for different types of products and firms.

The problem with this scheme is that it implies that overhead costs are directly proportional to the cost drivers. A thought experiment reveals that this cannot always be so: Most firms use "cost of purchased materials" as one cost driver, yet why would any of their overhead costs actually change if a vendor of a $50 component raises its price to $60? The answer is that they would not change at all. Overhead rates are used as a convenient way to account for overhead costs, but this scheme can yield inaccurate estimates of the true costs experienced by the manufacturer to support production.

This problem is partially addressed by activity-based costing (ABC) methods (Kaplan, 1990). Under the ABC approach, a firm utilizes more and different cost drivers and allocates all indirect costs to the associated cost drivers where they fit best. As a result, the firm may have overhead rates applied to various dimensions of product complexity (such as the number of different machining operations required or the number of different components or suppliers needed), in addition to overhead on tooling, materials, machine time, and direct labor. For the purposes of estimating manufacturing costs, the use of more cost drivers not only allows more accurate overhead cost estimates to be made but also provides important insights for reducing overhead costs by focusing attention on the cost drivers.

Step 2: Reduce the Costs of Components

For most highly engineered discrete goods the cost of purchased components will be the most significant element of the manufacturing cost. This section presents several strategies for minimizing these costs. Many of these strategies can be followed even without the benefit of accurate cost estimates. In this case, these strategies become *design rules,* or rules of thumb, to guide DFM cost reduction decisions.

Understand the Process Constraints and Cost Drivers

Some component parts may be costly simply because the designers did not understand the capabilities, cost drivers, and constraints of the production process. For example, a designer may specify a small internal corner radius on a machined part without realizing that physically creating such a feature requires an expensive electro-discharge machining (EDM) operation. A designer may specify dimensions with excessively tight tolerances, without understanding the difficulty of achieving such accuracy in production. Sometimes these costly part features are not even necessary for the component's intended function; they arise out of lack of knowledge. It is often possible to redesign the part to achieve the same performance while avoiding costly manufacturing steps; however, to do this the design engineer needs to know what types of operations are difficult in production and what drives their costs.

In some cases, the constraints of a process can be concisely communicated to designers in the form of design rules. For example, the capabilities of an automatic laser cutting machine for sheet metal can be concisely communicated in terms of allowable material types, material thicknesses, maximum part dimensions, minimum slot widths, and cutting accuracy. When this is possible, part designers can avoid exceeding the normal capabilities of a process and thereby avoid incurring unusually high costs.

For some processes, the cost of producing a part is a simple mathematical function of some attributes of the part, which would be the cost drivers for the process. For example,

EXHIBIT 13-9 Cost estimate for the redesigned intake manifold (two moldings).

Variable Cost		
Materials (manifold housing)	1.4 kg glass-filled nylon at $2.75/kg	$ 3.85
Materials (intake runner insert)	0.3 kg glass-filled nylon at $2.75/kg	0.83
Molding (manifold housing)	80 units/hr at $125/hr	1.56
Molding (intake runner insert)	100 units/hr at $110/hr	1.10
Fixed Cost		
Mold tooling (manifold housing)	$350,000/tool at 1.5M units/tool	$ 0.23
Mold tooling (intake runner insert)	$150,000/tool at 1.5M units/tool	0.10
Total Direct Cost		**$ 7.67**
Overhead charges		$ 5.99
Total Unit Cost		**$13.66**

a welding process could have a cost directly proportional to two attributes of the product: (1) the number of welds and (2) the total length of welds the machine creates.

For processes whose capabilities are not easily described, the best strategy is to work closely with the people who deeply understand the part production process. These manufacturing experts will generally have plenty of ideas about how to redesign components to reduce production costs.

Redesign Components to Eliminate Processing Steps

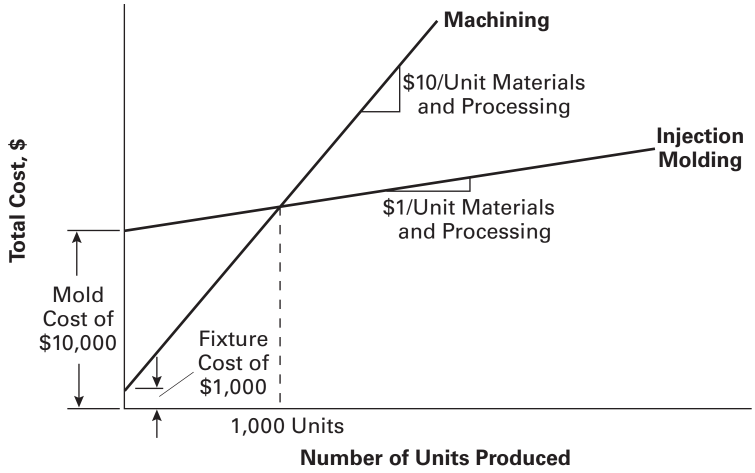
Careful scrutiny of the proposed design may lead to suggestions for redesign that can result in simplification of the production process. Reducing the number of steps in the part fabrication process generally results in reduced costs as well. Some process steps may simply not be necessary. For example, aluminum parts may not need to be painted, especially if they will not be visible to the user of the product. In some cases, several steps may be eliminated through substitution of an alternative process step. A common example of this strategy is "net-shape" fabrication. A net-shape process is one that produces a part with the final intended geometry in a single manufacturing step. Typical examples include molding, casting, forging, and extrusion. Frequently designers are able to use one of the net-shape processes to create a part that is very close to the final requirement (near net shape) and may demand only minor additional processing (e.g., drilling and tapping a hole, cutting to length).

The original intake manifold required an expensive casting, followed by several machining operations. The redesigned manifold is molded in two parts to net shape. The cost estimate for these two moldings is shown in Exhibit 13-9. (Compare with Exhibit 13-7.)

Choose the Appropriate Economic Scale for the Part Process

The manufacturing cost of a product usually drops as the production volume increases. This phenomenon is labeled *economies of scale.* Economies of scale for a fabricated component occur for two basic reasons: (1) fixed costs are divided among more units and (2) variable costs become lower because the firm can justify the use of larger and more efficient processes and equipment. For example, consider an injection-molded plastic part. The part may require a mold that costs $50,000. If the firm produces 50,000 units of the part over the product's lifetime, each part will have to assume $1 of the cost of the mold. If, however, 100,000 units are produced, each part will assume only $0.50 of the

EXHIBIT 13-10
Total cost of a hypothetical part as a function of the number of units produced for injection molding versus machining.



cost of the mold. As production volumes increase further, the firm may be able to justify a four-cavity mold, for which each cycle of the molding machine produces four parts instead of one. As shown in Exhibit 13-9, the tooling costs for the redesigned intake manifold are quite high; however, spread over the life of the tool, the unit fixed cost is small.

Processes can be thought of as incurring fixed and variable costs. Fixed costs are incurred once per part type regardless of how many parts are produced. Variable costs are incurred each time a part is made. Processes with inherently low fixed costs and high variable costs, such as machining, are appropriate when few parts will be made, while processes with inherently high fixed costs and low variable costs, such as injection molding, are appropriate when many parts will be made. This concept is illustrated by the graph in Exhibit 13-10. As shown in the exhibit, if production volume is expected to be below 1,000 units, machining would be more economical; otherwise, injection molding would incur lower total costs.

Standardize Components and Processes

The principle of economies of scale also applies to the selection of components and processes. As the production volume of a component increases, the unit cost of the component decreases. Quality and performance often increase as well with increasing production quantities because the producer of the component can invest in learning and improvement of the component's design and its production process. For a given expected product volume, the benefits of substantially higher component volumes can be achieved through the use of standard components.

Standard components are those common to more than one product. This standardization may occur within the product line of a single firm or may occur, via an outside supplier, across the product lines of several firms. For example, the use of the 3.8-liter V6 engine in several GM cars is an example of *internal standardization.* The use of a common 10-millimeter socket head cap screw across several auto manufacturers is an example of *external standardization*. In either case, all other things being equal, the component unit cost is lower than if the component were used in only a single product.

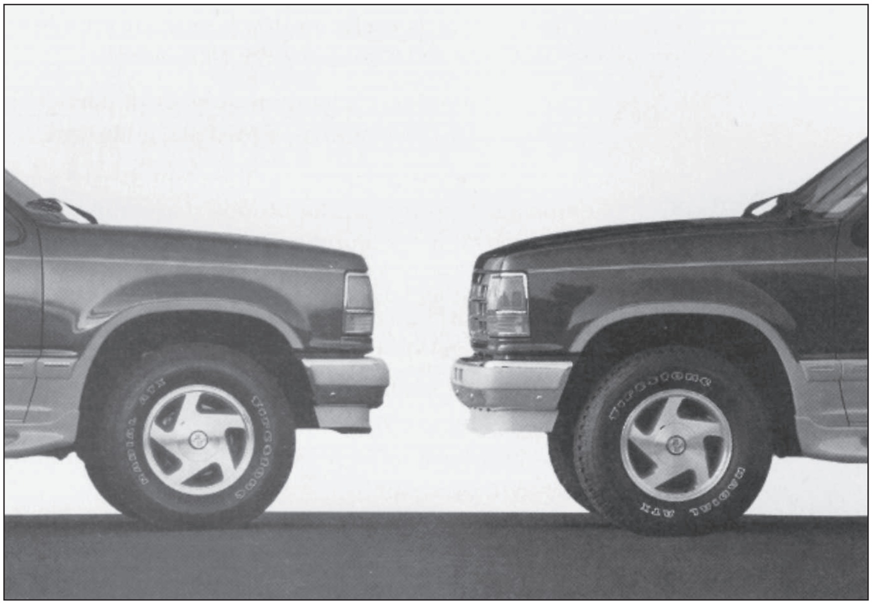


EXHIBIT 13-11
An example of standardization within a model. Wheels of the Ford Explorer are the same on the right and left sides of the car.

Courtesy of Ford Motor Co.

The redesigned intake manifold is used on all of GM's 3.8-liter V6 engines, even though each particular vehicle application requires different EGR (exhaust gas recirculation) return and vacuum hose routings. To accommodate this, the new intake manifold has two standard interfaces, a vacuum port and an EGR port. For each vehicle model, a custom vacuum block and EGR adapter are used. This allows the major component, the intake manifold, to be standardized internally, rather than using a different manifold for each vehicle.

Components may also be standardized within the same model. For example, most auto manufacturers use the same type of wheel on the right and left side of their cars, even though this causes directional "spokes" to have different orientations on different sides (Exhibit 13-11).

Adhere to "Black Box" Component Procurement

A component cost reduction strategy used effectively in the Japanese auto industry is called *black box* supplier design. Under this approach, the team provides a supplier with only a black box description of the component—a description of what the component has to do, not how to achieve it (Clark and Fujimoto, 1991). This kind of specification leaves the vendor with the widest possible latitude to design or select the component for minimum cost. An additional advantage of this approach is that it relieves the internal team of the responsibility to engineer and design the component. Successful black box development efforts require careful system-level design and extremely clear definitions of the functions, interfaces, and interactions of each component. (See Chapter 10, Product Architecture.)

For the redesigned intake manifold, the PCV valve assembly was designed by GM's AC Rochester Division, which supplies the component. The supplier was given system-level specifications and complete responsibility for the performance of this subsystem.

Step 3: Reduce the Costs of Assembly

Design for assembly (DFA) is a fairly well-established subset of DFM that involves minimizing the cost of assembly. For most products, assembly contributes a relatively small fraction of the total cost. Nevertheless, focusing attention on assembly costs yields strong indirect benefits. Often as a result of emphasis on DFA, the overall parts count, manufacturing complexity, and support costs are all reduced along with the assembly cost. In this section, we present a few principles useful to guide DFA decisions.

Keeping Score

Boothroyd and Dewhurst (1989) advocate maintaining an ongoing estimate of the cost of assembly. In addition to this absolute score, they propose the concept of *assembly efficiency*. This is measured as an index that is the ratio of the *theoretical minimum assembly time* to an estimate of the actual assembly time for the product. This concept is useful in developing an intuition for what drives the cost of assembly. The expression for the *DFA index* is

$$\text{DFA index} = \frac{(\text{Theoretical minimum number of parts}) \times (3 \text{ seconds})}{\text{Estimated total assembly time}}$$

To determine the theoretical minimum number of parts, ask the following three questions of each part in the proposed assembly. Only parts satisfying one or more of these conditions must "theoretically" be separate.

1. Does the part need to move relative to the rest of the assembly? Small motions that can be accomplished using compliance (e.g., elastic hinges or springs) do not count.
2. Must the part be made of a different material from the rest of the assembly for fundamental physical reasons?
3. Does the part have to be separated from the assembly for assembly access, replacement, or repair?

The "3 seconds" in the numerator reflects the theoretical minimum time required to handle and insert a part that is perfectly suited for assembly. One can think of this as the average time (sustainable over a whole work shift) required to assemble a small part that is easy to grasp, requires no particular orientation, and demands no special insertion effort; such an operation is as fast as placing a ball into a circular hole with adequate clearance.

Integrate Parts

If a part does not qualify as one of those theoretically necessary, then it is a candidate for physical integration with one or more other parts. The resulting multifunctional component is often very complex as a result of the integration of several different geometric features that would otherwise be separate parts. Nevertheless, molded or stamped parts can often incorporate additional features at little or no added cost. Exhibit 13-12 shows the throttle-body end of the redesigned intake manifold. Integrated into this component are the attachments for the EGR return and the vacuum source block. These attachments use a molded "push in and turn" geometry, eliminating the need for several threaded fasteners.

Part integration provides several benefits:

- Integrated parts do not have to be assembled. In effect, the "assembly" of the geometric features of the part is accomplished by the part fabrication process.

EXHIBIT 13-12
Integration of several features into a single component. The EGR return and vacuum source ports are molded into the redesigned intake manifold.

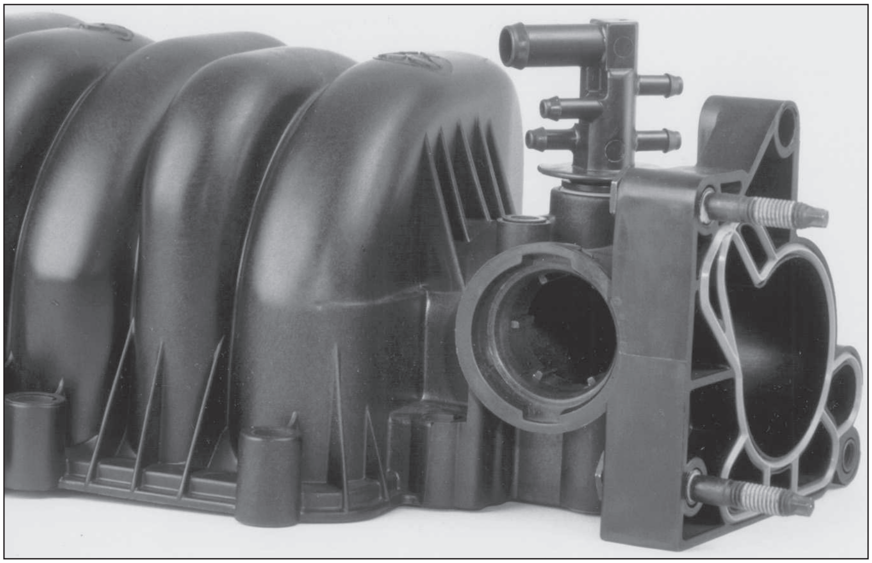


Photo by Stuart Cohen

- Integrated parts are often less expensive to fabricate than are the separate parts they replace. For molded, stamped, and cast parts, this cost savings occurs because a single complex mold or die is usually less expensive than two or more less complex molds or dies and because there is usually less processing time and scrap for the single, integrated part.
- Integrated parts allow the relationships among critical geometric features to be controlled by the part fabrication process (e.g., molding) rather than by an assembly process. This usually means that these dimensions can be more precisely controlled.

Note, however, that part integration is not always a wise strategy and may be in conflict with other sound approaches to minimizing costs. For example, the main intake manifold assembly on the old design was a single cast piece, requiring extensive machining. The team replaced this part with two less-expensive, injection-molded pieces. This is an example of disintegrating parts in order to achieve benefits in the piece-part production costs.

Maximize Ease of Assembly

Two products with an identical number of parts may nevertheless differ in required assembly time by a factor of two or three. This is because the actual time to grasp, orient, and insert a part depends on the part geometry and the required trajectory of the part insertion. The ideal characteristics of a part for an assembly are (adapted from Boothroyd and Dewhurst, 1989):

- ***Part is inserted from the top of the assembly.*** This attribute of a part and assembly is called *z-axis assembly.* By using z-axis assembly for all parts, the assembly never has to be inverted, gravity helps to stabilize the partial assembly, and the assembly worker can generally see the assembly location.

- ***Part is self-aligning.*** Parts that require fine positioning in order to be assembled require slow, precise movements on the part of the assembly worker. Parts and assembly sites can be designed to be self-aligning so that fine motor control is not required of the worker. The most common self-alignment feature is the *chamfer.* A chamfer can be implemented as a tapered lead on the end of a peg, or a conical widening at the opening of a hole.
- ***Part does not need to be oriented.*** Parts requiring correct orientation, such as a screw, require more assembly time than parts requiring no orientation, such as a sphere. In the worst case, a part must be oriented correctly in three dimensions. For example, the following parts are listed in order of increasing requirements for orientation: sphere, cylinder, capped cylinder, capped and keyed cylinder.
- ***Part requires only one hand for assembly.*** This characteristic relates primarily to the size of the part and the effort required to manipulate the part. All other things being equal, parts requiring one hand to assemble require less time than parts requiring two hands, which in turn require less effort than parts requiring a crane or lift to assemble.
- ***Part requires no tools.*** Assembly operations requiring tools, such as attaching snap rings, springs, or cotter pins, generally require more time than those that do not.
- ***Part is assembled in a single, linear motion.*** Pushing in a pin requires less time than driving a screw. For this reason, numerous fasteners are commercially available that require only a single, linear motion for insertion.
- ***Part is secured immediately upon insertion.*** Some parts require a subsequent securing operation, such as tightening, curing, or the addition of another part. Until the part is secured, the assembly may be unstable, requiring extra care, fixtures, or slower assembly.

Consider Customer Assembly

Customers may tolerate completing some of the product assembly themselves, especially if doing so provides other benefits, such as making the purchase and handling of the packaged product easier. However, designing a product such that it can be easily and properly assembled by the most inept customers, many of whom will ignore directions, is a substantial challenge in itself.

Step 4: Reduce the Costs of Supporting Production

In working to minimize the costs of components and the costs of assembly, the team may also achieve reductions in the demands placed on the production support functions. For example, a reduction in the number of parts reduces the demands on inventory management. A reduction in assembly content reduces the number of workers required for production and therefore reduces the cost of supervision and human resource management. Standardized components reduce the demands on engineering support and quality control. There are, in addition, some direct actions the team can take to reduce the costs of supporting production.

It is important to remember that manufacturing cost estimates are often insensitive to many of the factors that actually drive overhead charges. (Recall the discussion of overhead cost estimation above.) Nevertheless, the goal of the design team in this respect

Drivers of Complexity	**Rev. 1**	**Rev. 2**
Number of new parts introduced to the manufacturing system	6	5
Number of new vendors introduced to the manufacturing system	3	2
Number of custom parts introduced to the manufacturing system	2	3
Number of new "major tools" (e.g., molds and dies) introduced to the manufacturing system	2	2
Number of new production processes introduced to the manufacturing system	0	0
Total	**13**	**12**

EXHIBIT 13-13 Scorecard of manufacturing complexity.

should be to reduce the actual costs of production support even if overhead cost estimates do not change.

Minimize Systemic Complexity

An extremely simple manufacturing system would utilize a single process to transform a single raw material into a single part—perhaps a system extruding a single diameter of plastic rod from plastic pellets. Unfortunately, few such systems exist. Complexity arises from variety in the inputs, outputs, and transforming processes. Many real manufacturing systems involve hundreds of suppliers, thousands of different parts, hundreds of people, dozens of types of products, and dozens of types of production processes. Each variant of suppliers, parts, people, products, and processes introduces complexity to the system. These variants must usually be tracked, monitored, managed, inspected, handled, and inventoried at tremendous cost to the enterprise. Much of this complexity is driven by the design of the product and can therefore be minimized through smart design decisions.

Exhibit 13-13 shows a simple "scorecard" of manufacturing complexity useful for reminding designers of how the product design drives the complexity of the manufacturing system. The team establishes a score for the initial design and then uses changes in the score as a measure of success in reducing complexity. Note that the drivers given in the scorecard shown are generic categories. In practice, the team develops this list (and may prioritize it with weightings) based on the realities and constraints of the firm's production environment. Firms that use activity-based costing usually know quite well their primary drivers of complexity, as these are the cost drivers they use in allocating overhead. As a simple substitute for an accurate support cost model, such a scorecard allows the team to make informed decisions without formally estimating the indirect costs of production.

Error Proofing

An important aspect of DFM is to anticipate the possible failure modes of the production system and to take appropriate corrective actions early in the development process. This strategy is known as *error proofing.* One type of failure mode arises from having slightly different parts that can be easily confused. Examples of slightly different parts are screws differing only in the pitch of the threads (e.g., 4 × .70 mm and 4 × .75 mm screws) or in the direction of turning (left- and right-handed threads), parts that are mirror images of each other, and parts differing only in material composition.

We recommend either that these subtle differences be eliminated or that slight differences be exaggerated. Exhibit 13-14 shows an example of exaggerating subtle differences between parts: the left and right versions of the reel lock on a videocassette, which are

EXHIBIT 13-14
Left and right reel locks inside a videocassette (top center). The two nearly identical parts are color coded to avoid confusion.

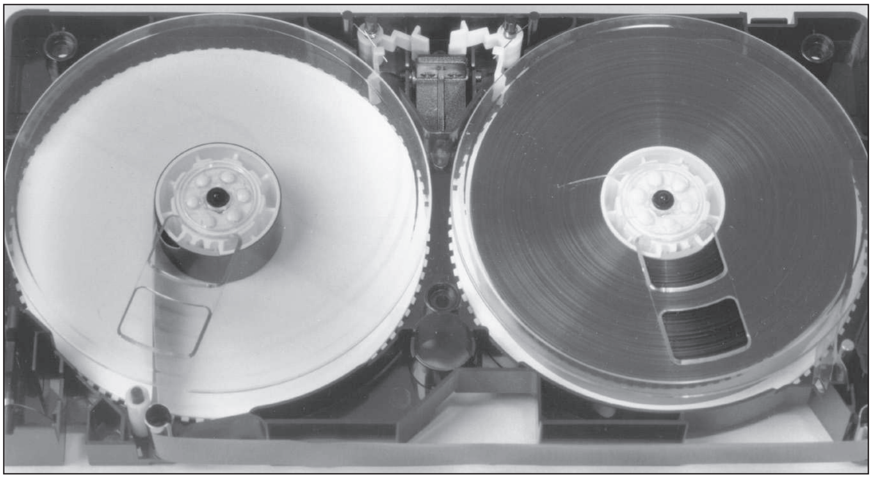


Photo by Stuart Cohen

mirror images of each other, are molded in two different colors. Color coding allows the parts to be identified easily and differentiated in materials handling and assembly.

Step 5: Consider the Impact of DFM Decisions on Other Factors

Minimizing manufacturing cost is not the only objective of the product development process. The economic success of a product also depends on the quality of the product, the timeliness of product introduction, and the cost of developing the product. There may also be situations in which the economic success of a project is compromised in order to maximize the economic success of the entire enterprise. In contemplating a DFM decision, these issues should be considered explicitly.

The Impact of DFM on Development Time

Development time can be precious. For an automobile development project, time may be worth as much as several hundred thousand dollars per day. For this reason, DFM decisions must be evaluated for their impact on development time as well as for their impact on manufacturing cost. While saving $1 in cost on each manifold would be worth perhaps $1 million in annual cost savings, it would almost certainly not be worth causing a six-month delay in an automobile program.

The relationship between DFM and development time is complex. Here, we note a few aspects of the relationship. The application of some of the DFA guidelines may result in very complex parts. These parts may be so complex that their design or the procurement of their tooling becomes the activity that determines the duration of the overall development effort (Ulrich et al., 1993). The cost benefits of the DFM decision may not be worth the delay in project duration. This is particularly true for products competing in dynamic markets.

The Impact of DFM on Development Cost

Development cost closely mirrors development time. Therefore, the same caution about the relationship between part complexity and development time applies to development cost. In general, however, teams that aggressively pursue low manufacturing costs as an integral part of the development process seem to be able to develop products in about the same time and with about the same budget as teams that do not. Part of this phenomenon certainly arises from the correlation between good project management practices and the application of sound DFM methods.

The Impact of DFM on Product Quality

Before proceeding with a DFM decision, the team should evaluate the impact of the decision on product quality. Under ideal circumstances, actions to decrease manufacturing cost would also improve product quality. For example, the new GM manifold resulted in cost reduction, weight reduction, and improved engine performance. It is not uncommon for DFM efforts focused primarily on manufacturing cost reduction to also result in improved serviceability, ease of disassembly, and recycling. However, in some cases actions to decrease manufacturing cost can have adverse effects on product quality (such as reliability or robustness), so it is advisable for the team to keep in mind the many dimensions of quality that are important for the product.

The Impact of DFM on External Factors

Design decisions may have implications beyond the responsibilities of a single development team. In economic terms, these implications may be viewed as externalities. Two such externalities are component reuse and life cycle costs.

- ***Component reuse:*** Taking time and money to create a low-cost component may be of value to other teams designing similar products. In general, this value is not explicitly accounted for in manufacturing cost estimates. The team may choose to take an action that is actually more costly for their product because of the positive cost implications for other projects.
- ***Life cycle costs:*** Throughout their life cycles, certain products may incur some company or societal costs that are not (or are rarely) accounted for in the manufacturing cost. For example, products may contain toxic materials requiring special handling in disposal. Products may incur service and warranty costs. Although these costs may not appear in the manufacturing cost analysis, they should be considered before adopting a DFM decision. Chapter 12, Design for Environment, provides a detailed method of addressing life cycle costs.

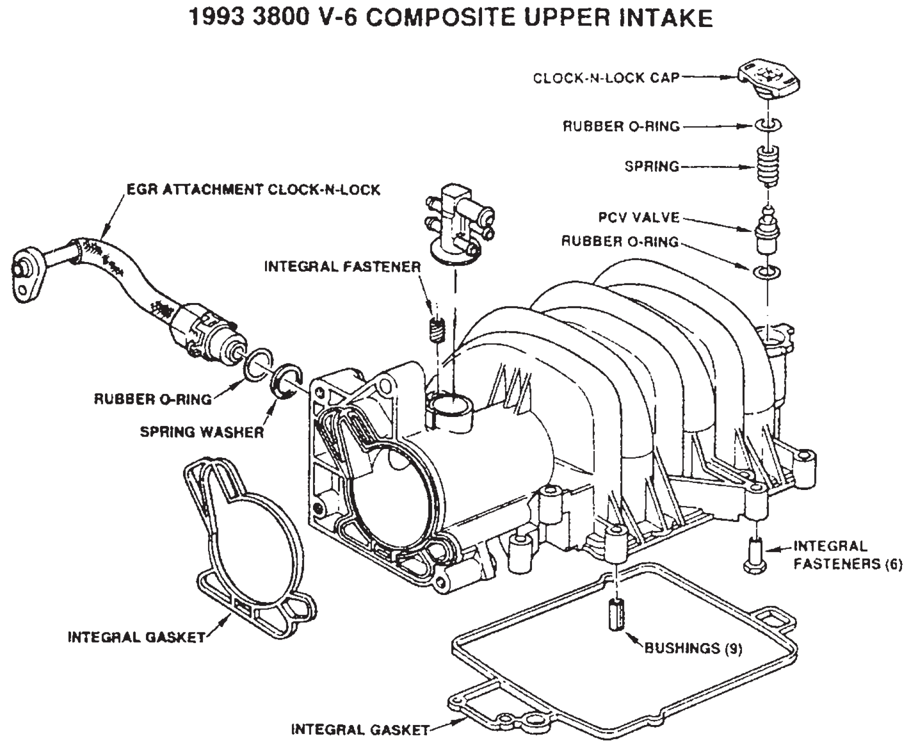
Results

During the 1980s, design-for-manufacturing practices were put into place in thousands of firms. Today DFM is an essential part of almost every product development effort. No longer can designers "throw the design over the wall" to production engineers. As a result of this emphasis on improved design quality, some manufacturers claim to have reduced production costs of products by up to 50 percent. In fact, comparing current new product designs with earlier generations, one can usually identify fewer parts in the new product, as well as new materials, more integrated and custom parts, higher-volume standard parts and subassemblies, and simpler assembly procedures.

A sketch of the redesigned intake manifold is shown in Exhibit 13-15. This DFM effort achieved impressive results. Exhibit 13-16 shows the cost estimate for the redesigned

EXHIBIT 13-15
The redesigned intake manifold.

Courtesy of General Motors Corp.



Component	Purchased Materials	Processing (Machine + Labor)	Assembly (Labor)	Total Unit Variable Cost	Tooling and Other NRE, K$	Tooling Lifetime, K units	Total Unit Fixed Cost	Total Cost
Manifold housing	3.85	1.56		5.41	350	1500	0.23	5.65
Intake runner insert	0.83	1.10	0.13	2.05	150	1500	0.10	2.15
Steel inserts (16)	0.32		1.00	1.32				1.32
EGR adapter	1.70		0.13	1.83				1.83
PCV valve								
Valve	0.85		0.04	0.89				0.89
O-rings(2)	0.02		0.16	0.18				0.18
Spring	0.08		0.10	0.18				0.18
Cover	0.02		0.10	0.12				0.12
Vacuum source block	0.04		0.06	0.10				0.10
Total Direct Costs	7.71	2.66	1.71	12.08	500		0.33	12.41
Overhead Charges	1.16	4.79	3.08				0.50	9.52
Total Cost								**21.93**

EXHIBIT 13-16 Cost estimate for the redesigned intake manifold.

intake manifold. (Compare with Exhibit 13-6.) The improvements over the previous design include:

- Unit cost savings of 45 percent.
- Mass savings of 66 percent (3.3 kilograms).
- Simplified assembly and service procedures.
- Improved emissions performance due to routing of EGR into the manifold.
- Improved engine performance due to reduced air induction temperatures.
- Reduced shipping costs due to lighter components.
- Increased standardization across vehicle programs.

For this product, the manufacturing cost savings alone amount to several million dollars annually. The other benefits listed above are also significant, although somewhat more difficult to quantify.

Summary

Design for manufacturing (DFM) is aimed at reducing manufacturing costs while simultaneously improving (or at least not inappropriately compromising) product quality, development time, and development cost.

- DFM begins with the concept development phase and system-level design phase; in these phases important decisions must be made with the manufacturing cost implications in mind.
- DFM utilizes estimates of manufacturing cost to guide and prioritize cost reduction efforts. Cost estimation requires expertise with the relevant production processes. Suppliers and manufacturing experts must be involved in this process.
- Since accurate cost estimation is very difficult, much of DFM practice involves making informed decisions in the absence of detailed cost data.
- Component costs are reduced by understanding what drives these costs. Solutions may involve novel component design concepts or the incremental improvement of existing designs through simplification and standardization.
- Assembly costs can be reduced by following well-established design-for-assembly (DFA) guidelines. Components can be redesigned to simplify assembly operations, or components can be eliminated entirely by integration of their functions into other components.
- Reduction of manufacturing support costs begins with an understanding of the drivers of complexity in the production process. Design decisions have a large impact on the costs of supporting production. Choices should be made with these effects in mind, even though overhead cost estimates are often insensitive to such changes.
- DFM is an integrative method taking place throughout the development process and requiring inputs from across the development team.
- DFM decisions can affect product development lead time, product development cost, and product quality. Trade-offs will frequently be necessary between manufacturing cost and these equally important broader issues.

References and Bibliography

Many current resources are available on the Internet via
www.ulrich-eppinger.net

Two articles describe the needs, methods, and success of DFM in the 1980s.

Dean, James W., Jr., and Gerald I. Susman, "Organizing for Manufacturable Design," *Harvard Business Review,* January–February 1989, pp. 28–36.

Whitney, Daniel E., "Manufacturing by Design," *Harvard Business Review,* July–August 1988, pp. 83–91.

There are numerous documented examples of DFM success. One classic example is the story of the IBM Proprinter, described by Dewhurst and Boothroyd.

Dewhurst, Peter, and Geoffrey Boothroyd, "Design for Assembly in Action," *Assembly Engineering,* January 1987.

There are many references available to aid in component design, materials choice, manufacturing process selection, and understanding of process capabilities. Here are several sources that offer specific guidelines for hundreds of applications, materials, and processes.

Bolz, Roger W., *Production Processes: The Productivity Handbook,* fifth edition, Industrial Press, New York, 1981.

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Cubberly, William H., and Ramon Bakerjian, *Tool and Manufacturing Engineers Handbook,* Society of Manufacturing Engineers, Dearborn, MI, 1989.

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Trucks, H. E., *Designing for Economical Production,* second edition, Society of Manufacturing Engineers, Dearborn, MI, 1987.

Gupta et al. provide a review of state-of-the-art manufacturability analysis methods and related DFM research.

Gupta, Satyandra K., et al., "Automated Manufacturability Analysis: A Survey," *Research in Engineering Design,* Vol. 9, No. 3, 1997, pp. 168–190.

The *Thomas Register* is useful for identifying suppliers of components, tooling, machinery, and other industrial products.

Thomas Register of American Manufacturers, Thomas Publishing Company, New York, published annually. Also available on the Internet.

The most popular method for DFA is by Boothroyd and Dewhurst. Software is also available to aid in estimating costs for both manual and automatic assembly, as well as a wide range of component costs.

Boothroyd, Geoffrey, and Peter Dewhurst, *Product Design for Assembly,* Boothroyd Dewhurst, Inc., Wakefield, RI, 1989.

Boothroyd, Geoffrey, Peter Dewhurst, and Winston A. Knight, *Product Design for Manufacture and Assembly,* second edition, Marcel Dekker, New York, 2002.

Detailed research on automated assembly has resulted in guidelines for designing products suited for assembly automation.

Boothroyd, Geoffrey, *Assembly Automation and Product Design,* Marcel Dekker, New York, 1992.

Nevins, James L., and Daniel E. Whitney, *Concurrent Design of Products and Processes,* McGraw-Hill, New York, 1989.

Whitney, Daniel E., *Mechanical Assemblies: Their Design, Manufacture, and Role in Product Development,* Oxford University Press, New York, 2004.

Kaplan and others describe the development of activity-based costing systems, which provide insight into a firm's cost drivers and facilitate more accurate cost estimation.

Kaplan, Robert S. (ed.), *Measures for Manufacturing Excellence,* Harvard Business School Press, Boston, 1990.

Clark and Fujimoto conducted a comprehensive study of product development in the world automobile industry. They provide an interesting analysis and discussion of the concept of black box component design.

Clark, Kim B., and Takahiro Fujimoto, *Product Development Performance: Strategy, Organization, and Management in the World Auto Industry,* Harvard Business School Press, Boston, 1991.

Ulrich et al. describe the trade-off between development time and manufacturing cost. They also describe an effort to model support costs in some detail.

Ulrich, Karl, Scott Pearson, David Sartorius, and Mark Jakiela, "Including the Value of Time in Design-for-Manufacturing Decision Making," *Management Science,* Vol. 39, No. 4, April 1993, pp. 429–447.

Ulrich and Pearson present a method for studying products, their costs, and some of the many detail design decisions resulting in the artifacts we see.

Ulrich, Karl T., and Scott Pearson, "Assessing the Importance of Design through Product Archaeology," *Management Science,* Vol. 44, No. 3, March 1998, pp. 352–369.

Exercises

1. Estimate the production cost for a simple product you may have purchased. Try costing a product with fewer than 10 components, such as a floppy disk, a pen, a jackknife, or a baby's toy. Remember that one reasonable upper bound for your estimate, including overhead, is the wholesale price (between 50 percent and 70 percent of retail).
2. Suggest some potential cost-reducing modifications you could make to improve the product costed above. Compute the DFA index before and after these changes.
3. List 10 reasons why reducing the number of parts in a product might reduce production costs. Also list some reasons why costs might increase.

Thought Questions

1. Consider the following 10 "design rules" for electromechanical products. Do these seem like reasonable guidelines? Under what circumstances could one rule conflict with another one? How should such a trade-off be settled?
   a. Minimize parts count.
   b. Use modular assembly.
   c. Stack assemblies.
   d. Eliminate adjustments.
   e. Eliminate cables.
   f. Use self-fastening parts.
   g. Use self-locating parts.
   h. Eliminate reorientation.
   i. Facilitate parts handling.
   j. Specify standard parts.
2. Is it practical to design a product with 100 percent assembly efficiency (DFA index = 1.0)? What conditions would have to be met? Can you think of any products with very high (greater than 75 percent) assembly efficiency?
3. Is it possible to determine what a product really costs once it is put into production? If so, how might you do this?
4. Can you propose a set of metrics that would be useful for the team to predict changes in the actual costs of supporting production? To be effective, these metrics must be sensitive to changes in the design that affect indirect costs experienced by the firm. What are some of the barriers to the introduction of such techniques in practice?

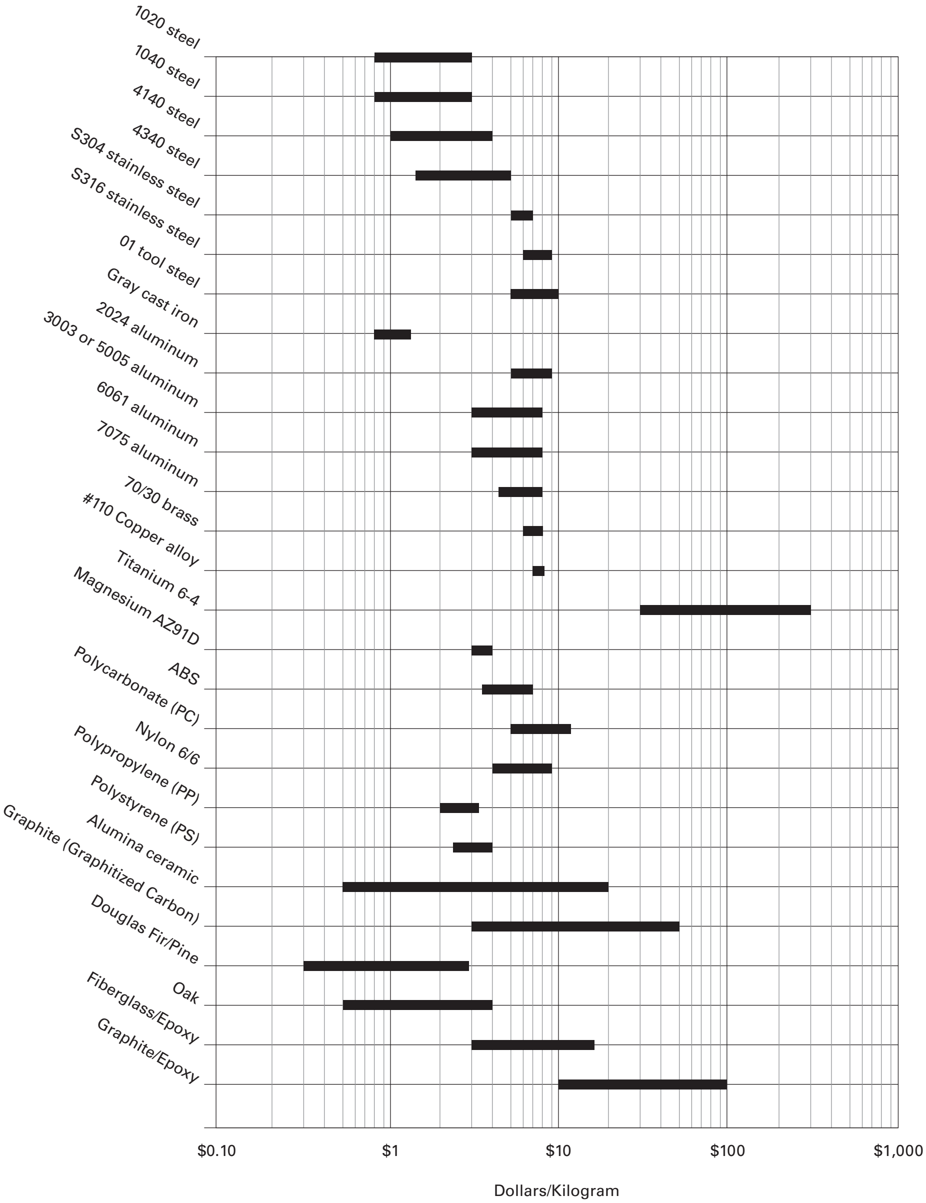
Appendix A

Materials Costs

EXHIBIT 13-17

Range of costs for common engineering materials. Price ranges shown correspond to various grades and forms of each material, purchased in bulk quantities (2011 prices).

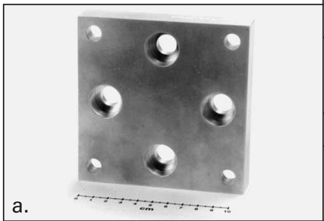
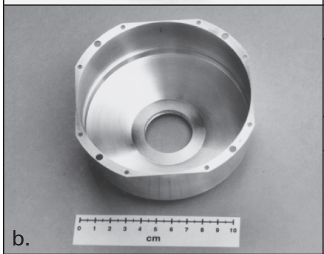
Source: Adapted from David G. Ullman, *The Mechanical Design Process,* third edition, McGraw-Hill, New York, 2003



Appendix B

Component Manufacturing Costs

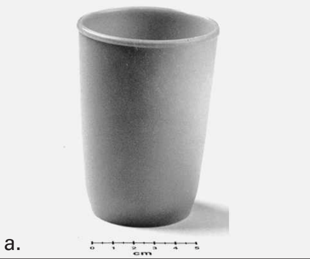
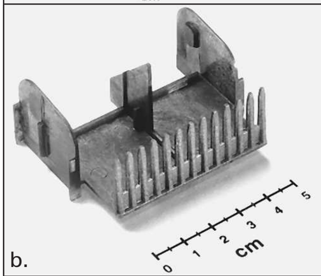
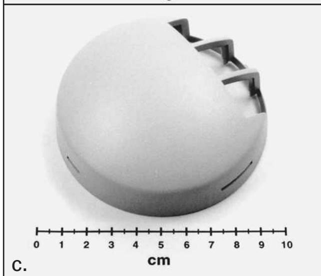
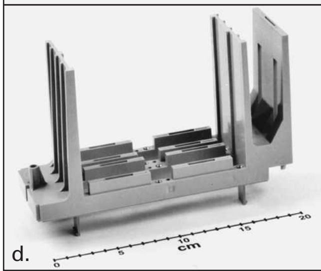
The exhibits in this appendix show example components and their cost data for computer-numerical control (CNC) machining (Exhibit 13-18), injection molding (Exhibit 13–19), progressive die stamping (Exhibit 13-20), and sand casting and investment casting (Exhibit 13-21). The purpose of these examples is to show, in general terms, what typical operations cost and how the cost structure of each process is affected by part complexity.

	Fixed Costs	*Variable Costs*	*Volume*	*Total Unit Cost*
 a.	Setup: 0.75 hr. at $60/hr. Tooling: programming: 0.25 hr. at $60/hr.	Material: $9 ea. stock: 1.11 kg of 6061 aluminum Processing: 6 min./unit at $60/hr.	1 10 100	$75.00 $21.00 $15.50
 b.	Setup: 1.75 hr. at $60/hr. Tooling: programming: 1.0 hr. at $60/hr. Fixtures: $150	Material: $16 ea. stock: 1.96 kg of 6061 aluminum Processing: 55 min./unit at $60/hr.	1 10 100	$386.00 $102.50 $74.15
 c.	Setup: 5.5 hr. at $60/hr. Tooling: programming: 2.0 hr. at $60/hr.	Material: $25 ea. stock: 4.60 kg of ultra-high molecular weight polyethylene Processing: 2.85 hr./unit at $60/hr.	1 10 100	$646.00 $241.00 $200.50
 d.	Setup: 2.0 hr. at $60/hr. Tooling: programming: 2.0 hr. at $60/hr.	Material: $12 ea. stock: 1.50 kg of 6061 aluminum Processing: 6 hr./unit at $60/hr.	1 10 100	$612.00 $396.00 $374.40

Source: Photos by Stuart Cohen. Examples and data courtesy of Ramco, Inc.

Notes: 1. Programming time is a one-time expense and is included here in tooling costs.
2. Material prices assume low volumes and include cutting charges.
3. Processing costs include overhead charges.

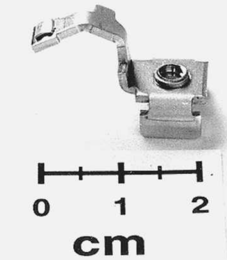
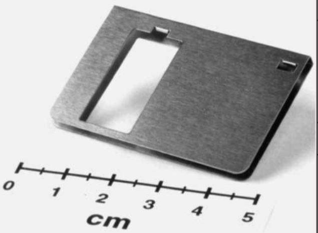
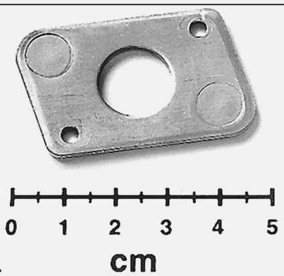
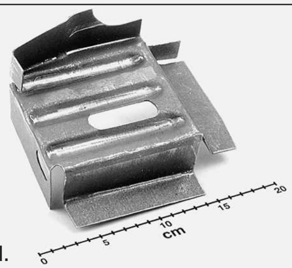
EXHIBIT 13-18 **CNC machining cost examples**
CNC machining example components and cost data.

	Fixed Costs	Variable Costs	Volume	Total Unit Cost
 a.	Setup:	Material: $0.075 ea. 45 g of linear low density polyethylene (LLDPF)	10K 100K 1M	$1.915 $0.295 $0.133
	Tooling: $18K 8 cavities/mold no actions	Processing: 1000 pcs/hr. on an 1800 KN press at $40/hr.		
 b.	Setup:	Material: $0.244 ea. 10 g of steel-filled polycarbonate (PC)	10K 100K 1M	$1.507 $0.607 $0.517
	Tooling: $10K 1 cavity/mold no actions	Processing: 160 pcs/hr. on a 900 KN press at $42/hr.		
 c.	Setup:	Material: $0.15 ea. 22 g of modified polyphenylene oxide (PPO)	10K 100K 1M	$2.125 $0.505 $0.343
	Tooling: $18K 2 cavities/mold no actions 3 retracting pins	Processing: 240 pcs/hr. on an 800 KN press at $42/hr.		
 d.	Setup:	Material: $2.58 ea. 227 g of polycarbonate (PC) with 8 brass inserts	10K 100K 1M	$11.085 $3.885 $3.165
	Tooling: $80K 1 cavity/mold 1 action 4 retracting pins	Processing: 95 pcs/hr. on a 2700 KN press at $48/hr.		

Source: Photos by Stuart Cohen. Examples and data courtesy of Lee Plastics, Inc., and Digital Equipment Corporation

Notes: 1. Setup costs (only a few hours in each case) are negligible for high-volume injection molding.
2. Processing costs include overhead charges.

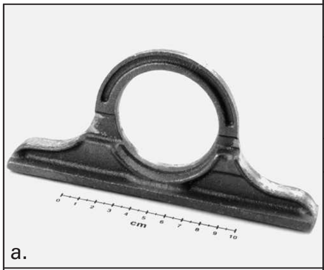
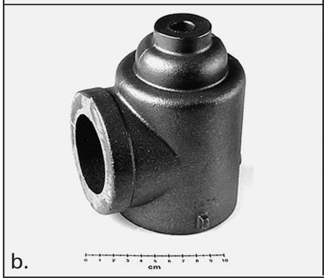
EXHIBIT 13-19 **Injection molding cost examples**
Injection molding example components and cost data.

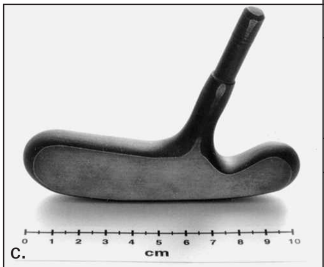
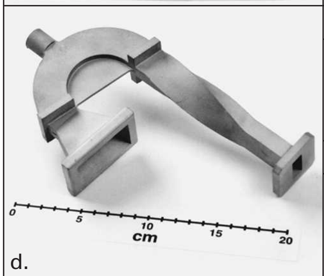
	Fixed Costs	*Variable Costs*	*Volume*	*Total Unit Cost*
 a.	Setup: Tooling: $22K	Material: $0.040 ea. 2.2g 70/30 Brass Processing: 3000 pcs/hr. on a 550 KN press at $63/hr.	100K 1M 10M	$0.281 $0.083 $0.063
 b.	Setup: Tooling: $71K	Material: $0.032 ea. 3.5 g 304 SST Processing: 4300 pcs/hr. on a 550 KN press at $140/hr.	100K 1M 10M	$0.775 $0.136 $0.072
 c.	Setup: Tooling: $11K	Material: $0.128 ea. 19.2 g 102 copper Processing: 4800 pcs/hr. on a 650 KN press at $50/hr.	100K 1M 10M	$0.248 $0.149 $0.140
 d.	Setup: Tooling: $195K	Material: $0.28 ea. 341 g galvanized steel Processing: 700 pcs/hr. on a 1000 KN press at $200/hr.	100K 1M 10M	$2.516 $0.761 $0.585

Source: Photos by Stuart Cohen. Examples and data courtesy of Brainin Advance Industries and other sources

Notes: 1. Setup costs (only a few hours in each case) are negligible for high-volume stamping.
2. Material weights represent the finished stampings. Material costs include scrap.
3. Hourly processing costs are not only driven by press size, but also can include ancillary processing equipment, such as in-die tapping.
4. Processing costs include overhead charges.

EXHIBIT 13-20 **Stamping cost examples**
Volume progressive die stamping example components and cost data.

	Fixed Costs	***Variable Costs***	***Volume***	***Total Unit Cost***
 a.	Setup: Tooling: $1.8K 8 impressions/pattern no core	Material: $0.53 ea. 570 g of gray cast iron Processing: 120 pcs/hr. at $46/hr.	10 100 1000	$180.91 $18.91 $2.71
 b.	Setup: Tooling: $2.4K 2 impressions/pattern 1 core	Material: $2.42 ea. 2,600 g of gray cast iron Processing: 30 pcs/hr. at $46/hr.	10 100 1000	$243.95 $27.95 $6.35

	Fixed Costs	***Variable Costs***	***Volume***	***Total Unit Cost***
 c.	Setup: Tooling: $1.5K no cores	Material: $0.713 ea. 260 g of yellow brass Processing: 4 pcs/hr. at $50/hr.	10 100 1000	$163.21 $28.21 $14.71
 d.	Setup: Tooling: $7K 3 cores	Material: $0.395 ea. 180 g of 712 aluminum Processing: 1 pc/hr. at $50/hr.	10 100 1000	$750.40 $120.40 $57.40

Source: Photos by Stuart Cohen. Examples and data courtesy of Cumberland Foundry Co., Inc. (sand casting), and Castronics, Inc. (investment casting)

Notes: 1. Setup is not generally charged in costing.
2. Processing costs include overhead charges.

EXHIBIT 13-21 Casting cost examples
Sand casting (top) and investment casting (bottom) example components and cost data.

Terminology

The following terminology applies to all of the tables in this appendix:

- ***Setup*** is the work required to prepare the equipment for a production run. Setup costs are charged for each run.
- ***Tooling costs*** are incurred in advance of the first production run, and tooling can usually be reused for later production runs. However, in very high-volume production runs, tooling wears out and therefore is a recurring expense. Tooling costs may be spread over the entire production volume or may be charged separately. CNC programming time is generally also a one-time expense, like a tooling cost.
- ***Material types*** are listed for each part. Material weights and costs include processing scrap and waste.
- ***Processing costs*** vary with the type of manufacturing equipment used and include charges for both machine time and labor.

While fixed costs (setup and tooling) are sometimes billed separately from material and processing costs, for these examples, fixed costs are spread over the production volume shown. Unit costs are calculated as

$$\text{Total unit cost} = \frac{\text{Setup costs} + \text{Tooling costs}}{\text{Volume}} + \text{Variable costs}$$

The cost rates given include overhead charges, so these data are representative of custom components purchased from suppliers.

Description of Processes

CNC machining includes computer-controlled milling and turning processes. CNC machines are highly flexible due to automatic tool-changing mechanisms, multiple work axes, and programmable computer control. To produce a particular part, a machinist must first program the cutting tool trajectories and tool selections into the machine's computer. Also, fixtures or other tooling may be utilized to produce multiple parts more efficiently. Once the program is written and fixtures are made, subsequent production runs can be set up much more quickly.

Injection molding is the process of forcing hot plastic under high pressure into a mold, where it cools and solidifies. When the part is sufficiently cool, the mold is opened, the part is ejected, the mold closes, and the cycle begins again. Mold complexity depends highly on the part geometry; undercuts (features that would prevent the part from ejecting out of the mold) are achieved using mold "actions" or "retracting pins."

Progressive die stamping is the process of passing a sheet or strip of metal through a set of dies to cut and/or form it to a desired size and shape. While some stampings require only cutting, formed stampings are made by bending and stretching the metal beyond its yield point, thereby causing permanent deformation.

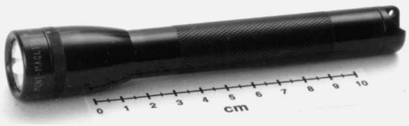
Sand castings are created by forming a sand mold from master patterns (tooling in the shape of the final part). Special binders are mixed with the sand to allow the sand to retain shape when packed around the pattern to create a single-use mold. Internal cavities in a casting can be created using additional sand cores inside the outer mold. Molten metal is then poured into the mold where the metal cools and solidifies. Once cool, the sand is broken off to reveal the metal casting. Sand castings generally require subsequent machining operations to create finished components.

Investment castings are made by first creating a temporary wax pattern, using master tooling. The wax pattern is then dipped or immersed in plaster or ceramic slurry, which is allowed to solidify. The form is then heated, melting out the wax and leaving behind only the thin shell as a mold. Molten metal is then poured into the mold, where it cools and solidifies. When the metal is cool, the mold is broken off to reveal the metal part.

Detailed process descriptions for the above and numerous other processes, as well as more detailed cost estimating techniques, can be found in the reference books listed for this chapter.

Appendix C

Assembly Costs

Product	***Part Data***	***Assembly Times (Seconds)***
	No. of Parts: 16	Total: 125.7
	No. of Unique Parts: 12	Slowest Part: 9.7
	No. of Fasteners: 0	Fastest Part: 2.9
	No. of Parts: 34	Total: 186.5
	No. of Unique Parts: 25	Slowest Part: 10.7
	No. of Fasteners: 5	Fastest Part: 2.6
	No. of Parts: 49	Total: 266.0
	No. of Unique Parts: 43	Slowest Part: 14.0
	No. of Fasteners: 5	Fastest Part: 3.5
	No. of Parts: 56/17*	Total: 277.0/138.0*
	No. of Unique Parts: 44/12*	Slowest Part: 8.0/8.0*
	No. of Fasteners: 0/0*	Fastest Part: 0.75/3.0*

Source: Photos by Stuart Cohen. Data obtained by using Boothroyd Dewhurst Inc. DFA software

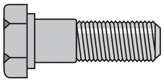
*Data for the mouse are given as: total components (including electronic)/mechanical components only.

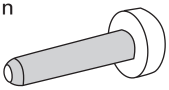
Notes: 1. This table gives manual assembly times, which can be converted to assembly costs using applicable labor rates.

2. Assembly times shown include times for individual part handling and insertion, as well as other operations such as subassembly handling and insertion, reorientations, and heat riveting.

EXHIBIT 13-22 **Assembly costs**

Assembly data for common products. Obtained using Boothroyd Dewhurst Inc. DFA Software.

Component	Time (Seconds)		
	Min	*Max*	*Avg*
Screw 	7.5	13.1	10.3
Snap-fit 	3.5	8.0	5.9

Component	Time (Seconds)		
	Min	*Max*	*Avg*
Pin 	3.1	10.1	6.6
Spring 	2.6	14.0	8.3

Source: Manual assembly tables in Boothroyd and Dewhurst, 1989

EXHIBIT 13-23 Typical handling and insertion times for common components.

Appendix D

Cost Structures

Type of Firm	Cost Calculation
Electromechanical products manufacturer (Traditional cost structure)	Cost = (113%) × (Materials cost) + (360%) × (Direct labor cost)
Precision valve manufacturer (Activity-based cost structure)	Cost = (108%) × [(Direct labor cost) + (Setup labor cost) + (160%) × (Materials cost) + ($27.80) × (Machine hours) + ($2,000.00) × (Number of shipments)]
Heavy equipment component manufacturer (Activity-based cost structure)	Cost = (110%) × (Materials cost) + (109%) × [(211%) × (Direct labor cost) + ($16.71) × (Machine hours) + ($33.76) × (Setup hours) + ($114.27) × (Number of production orders) + ($19.42) × (Number of material handling loads) + ($487.00) × (Number of new parts added to the system)]

Sources, top to bottom: Unpublished company source; Harvard Business School cases: Destin Brass Products Co., 9-190-089, and John Deere Component Works, 9-187-107

Notes: 1. This table shows total costs per customer order.
2. Materials costs include costs of raw materials and purchased components.

EXHIBIT 13-24 Typical cost structures for manufacturing firms.